Identification of Transverse Crack in a Cracked Cantilever Beam Using Fuzzy Logic and Kohonen Network

A Thesis Submitted in Partial Fulfillment of the Requirements for the Award of the Degree of

Master of Technology

in

Mechanical Engineering

(Machine Design & Analysis)

by

Sasanka Choudhury

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NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

राष्ट्रीय प्रौद्योगिकी संस्थान राउरकेला

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To Bhagawan Shri Sathyasai Baba & My beloved Parents

National Institute of Technology Rourkela

Certificate

This is to certify that the thesis entitled, "***Identification of Transverse Crack in a Cracked Cantilever Beam using Fuzzy Logic and Kohonen Network***" submitted by ***Mr. Sasanka Choudhury*** to National Institute of Technology Rourkela, is a record of bonafide research work carried out by him under my supervision and is worthy of consideration for the award of the degree of **Masters of Technology** in Mechanical Engineering with specialization in **Machine Design and Analysis.** The embodiment of this thesis has not been submitted to any other University and/or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENT

First, I offer my humble pranam on the lotus feet of Bhagawan Sri Sathya Sai Baba for his subtle support in all difficulties through out my life. Its my wishes to express my gratitude towards my parents for their eternal effort.

I would like to express my greatest appreciation to my supervisor Dr. Dayal Ramakrushna Parhi for his encouragement and guidance, timely suggestions during the completion of the project. The discussions held with him during the research work, which helped me a lot in materializing this dissertation work and also to grow up my knowledge. My sincere thank also to Prof. R. K. Sahoo and Prof. N. Kavi, for their valuable suggestions and comments. I mention the help and support received from my dearest friends. The guidance and support received from all the members who contributed and who else part of this project, whose names could have not been mentioned here, is highly acknowledged.

I owe my indebtedness to my younger brother Satish and elder brother Sanjib for their moral support and encouragement. Last but not least, I deeply appreciate the help and guidance of Prof. Sarat Kumar Patra in every time I need during my stay at NIT Rourkela.

Sasanka Choudhury

ABSTRACT

The issue of crack detection and diagnosis has gained wide spread industrial interest. Crack/damage affects the industrial economic growth. Generally damage in a structural element may occur due to normal operations, accidents, deterioration or severe natural events such as earth quake or storms. Damage can be analyzed through visual inspection or by the method of measuring frequency, mode shape and structural damping. Damage detection by visual inspection is a time consuming method and measuring of mode shape as well as structural deflection is difficult rather than measuring frequency. As Non-destructive method for the detection of crack is favorable as compared to destructive methods. So, our analysis has been made on the basis of non-destructive methods with the consideration of natural frequency. Here the crack is transverse surface crack. In the current analysis, methodologies have been developed for damage detection of a cracked cantilever beam using analytical, fuzzy logic, kohonen network as well as experimental. Theoretical analysis has been carried out to calculate the natural frequency with the consideration of mass and stiffness matrices. The data obtained from theoretical analysis has been fed to fuzzy controller as well as the kohonen competitive learning network.

The Fuzzy Controller uses the different membership functions as input as well as output. The input parameters to the Fuzzy Controller are the first three natural frequencies. The output parameters of the fuzzy controller are the relative crack depth and relative crack location. Several Fuzzy rules have been trained to obtain the results for relative crack depth and relative crack location.

Kohonen network is nothing but a competitive learning network is used here for the detection of crack depth and location. It is processed through a vector quantization algorithm.

A comparative study has been made between fuzzy logic technique and Kohonen network technique after experimental verification. It has been observed that the process of kohonen network can predict the depth and location accurately as close to fuzzy logic technique.

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NOMENCLATURE

a_1	= Depth of crack
A	= Cross-sectional area of the beam
A_i i = 1to 12	= Unknown coefficients of matrix A
B	= Width of the beam
B_1	= Vector of exciting motion
C_u	$= (\frac{E}{\rho})^{1/2}$
C_y	$= (\frac{EI}{\mu})^{1/2}$
E	= Young's modulus of elasticity of the beam material
fnf	= Relative first natural frequency
F_i i = 1, 2	= Experimentally determined function
i, j	= Variables
J	= Strain-energy release rate
$K_{1,i}$ i = 1, 2	= Stress intensity factors for P_i loads
$\overline{K}_u$	$= \frac{\omega L}{C_u}$
$\overline{K}_y$	$= \left(\frac{\omega L^2}{C_y}\right)^{1/2}$
K_{ij}	= Local flexibility matrix elements
L	= Length of the beam
L_1	= Location (length) of the crack from fixed end
M_i i=1, 4	= Compliance constant
P_i i=1, 2	= Axial force (i=1), bending moment (i=2)
Q	= Stiff-ness matrix for free vibration.
Q_1	= Stiff-ness matrix for forced vibration
rcd	= Relative crack depth
rcl	= Relative crack location

snf = Relative second natural frequency

tnf = Relative third natural frequency

u_i i=1, 2 = Normal functions (longitudinal) $u_i(x)$

x = Co-ordinate of the beam

y = Co-ordinate of the beam

Y_0 = Amplitude of the exciting vibration

y_i i=1, 2 = Normal functions (transverse) $y_i(x)$

W = Depth of the beam

ω = Natural circular frequency

β = Relative crack location $\frac{L_1}{L}$

μ = $A\rho$

ρ = Mass-density of the beam

ξ_1 = Relative crack depth $\frac{a_1}{W}$

V = Aggregate (union)

Λ = Minimum (min) operation

$\forall$ = For every

$\arg_j \max$ = Argument of maximum value

$\arg_j \min$ = Argument of minimum value

$\vec{x}$ = Input vector

$\lfloor \vec{w}_j \rfloor$ = Weight Vector

$h_{j,i}(\vec{x}) = \exp\left(\frac{-d^2_{j,i}}{2\sigma^2}\right)$

$h_{j,i}(\vec{x})$ =Neighborhood Function

$d_{j,i}$ = Lateral distance between the winning neuron 'i' and excited neuron j

σ =Width of Gaussian function

$\sigma(t) = \sigma_0 \exp\left(-\frac{t}{\tau_1}\right)$

τ_1 = Time Constant

t = Number of iterations

$\eta(t)$ = Learning Rate

τ_2 = Time Constant

BMU = Best Matching Unit

CHAPTER 1

INTRODUCTION

1.1. Theme of Thesis

1.2. Motivation of Work

1.3. Thesis Layout

CHAPTER 1

Introduction

1.1. Theme of Thesis

Damage is one of the important aspects in structural analysis because of safety reason as well as economic growth of the industries. Generally damage in a structural element may occur due to normal operations, accidents, deterioration or severe natural events such as earth quake or storms. To achieve their industrial goal, now a days the plants as well as industries are running round the clock fully. During operation, all structures are subjected to degenerative effects that may cause initiation of structural defects such as cracks which, as time progresses, lead to the catastrophic failure or breakdown of the structure. Thus, the importance of inspection in the quality assurance of manufactured products is well understood. To avoid the unexpected or sudden failure earlier crack detection is essential. Taking this ideology into consideration crack detection is one of the most important domains for many researchers. This is basically appears in the vibrating structures while undergoes operations. The most common structural defect is the existence of a crack in machine member. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent.

It has been observed that for damage/crack detection non-destructive testing is preferable over destructive testing. Many researchers have carried out different non-destructive methodologies for crack detection but it has been observed that the vibration based method is fast and inexpensive for crack/damage identification. Vibration- based methods can be classified into two categories: linear and nonlinear approaches. Linear approaches detect the presence of cracks in a target object by monitoring changes in the resonant frequencies in the mode shapes or in the damping factors. Depending on the assumptions, the type of analysis, the overall beam characteristics and the kind of loading or excitation, a number of research papers containing a variety of different approaches have been reported in the relevant literature. Damage can be analyzed through visual inspection or by the method of measuring frequency, mode shape and structural damping. Damage detection by visual inspection is a time consuming method and measuring of mode shape as well as structural deflection is difficult rather than measuring frequency. The presence of crack induces local flexibility, which affects the dynamic behavior of the whole structure as a result the reduction occurs in natural frequency and mode shape. By considering the changes in those parameters crack can be identified in terms of crack depth and crack location.

Many researches have been carried out their research works using open crack models, which means they have considered that a crack remains open during vibration. The assumption of an open crack leads to a constant shift of natural frequencies of vibration. Numerous methodologies investigated over last few decades, however, indicate that a real fatigue crack opens and closes during vibration. It exhibits non-linear behavior due to the variation of the stiffness which occurs during the response cycle. As a result, a breathing crack gives rise to natural frequencies falling between those corresponding to the open and closed states. Therefore, if an always open crack is assumed, the decrease in experimental natural frequencies will lead to an underestimation of the crack depth.

Beams are one of the most commonly used structural elements in several engineering applications and experience a wide variety of static and dynamic loads. Cracks may develop in beam-like structures due to such loads. Considering the crack as a significant form of such damage, its modeling is an important step in studying the behavior of damaged structures. Knowing the effect of crack on stiffness, the beam or shaft can be modeled using either Euler-Bernoulli or Timoshenko beam theories. The beam boundary conditions are used along with the crack compatibility relations to derive the characteristic equation relating the natural frequency, the crack depth and location with the other beam properties.

In the past few years the problem of health monitoring and fault detection of structures has received considerable deliberation. The changes can be considered as an indication of the health of the structure. Subsequently, these methods of fault detection are based on the comparison of the vibrant response of the healthy structure with the active response of the deserted structure. The evaluation is carried out through some algorithm, which employs the modal data of the healthy and deserted structure. Therefore, the fault detection problem is in need of the modal data for the healthy structure, the modal data for the deserted structure and the algorithm that uses these data and provides information about the state of the structure. Each of these items has its own aspects and associated problems that affect the results of the fault detection.

The most common structural defect is the existence of a crack. Cracks are present in structures due to various reasons. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent. Cracks present in vibrating/rotating components could lead to catastrophic failure. They may also occur due to mechanical defects. Another group of cracks are initiated during the manufacturing processes. Generally they are small in sizes. Such small cracks are known to propagate due to fluctuating stress conditions. If these propagating cracks remain undetected and reach their critical size, then a sudden structural failure may occur. Hence it is possible to use natural frequency measurements to detect cracks. To help in a continuous safety assessment of a machine or structure it is very necessary to constantly assess the health of its critical components. This calls for a continuous assessment of changes in their static and/or dynamic behavior. The development of a crack does not necessarily make a component instantly useless, but it is a signal that its behavior has to be monitored more carefully. Such monitoring can play a significant role in assuring an uninterrupted operation in service by the component.

A direct procedure is difficult for crack identification and unsuitable in some particular cases, since they require minutely detailed periodic inspections, which are very costly. In order to avoid these costs, researchers are working on more efficient procedure in crack detection through vibration analysis.

1.2. Motivation of Work

The main objective of the present research work is to develop an organized structure for damage detection of a cracked cantilever beam using fuzzy logic technique as well as kohonen network technique. These techniques are usually called the intelligent techniques because the techniques can be processed without human intervention.

It is necessary that structures must safely work during its service life but, damages initiate a breakdown period on the structures which directly affect the industrial growth. It is a recognized fact that dynamic behavior of structures changes due to presence of crack. It has been observed that the presence of cracks in structures or in machine members lead to operational problem as well as premature failure. A number of researchers around the earth are working on structural dynamics and particularly on dynamic characteristics of structures with the presence of crack. The information available on dynamic characteristics of crack is not so exhaustive for real application. Therefore an effort has been given to formulate some Intelligent Techniques for localization and identification of crack in cantilever beam structures. Due to presence of cracks the dynamic characteristics of structure changes. The change in dynamic behavior has been utilized as one of the criteria of fault diagnosis for structures. Major characteristics of the structure which undergo change due to presence of crack are; natural frequencies, the amplitude responses due to vibration and the mode shapes. The phases of the process plan for the present investigation are as follows:

- ✓ Theoretical expressions have been developed for free and forced Vibration analysis of the single cracked cantilever beam for the detection of crack depth and crack location. In all these theoretical approach transverse crack has been analyzed.
- ✓ Experimental Analysis has been performed to obtain the relative values of first, second and third modal natural frequencies.
- ✓ The data obtained from the theoretical as well as experimental analysis has been trained to fuzzy controller for designing the rule base for the detection of crack depth and crack location.
- ✓ Using the same data the kohonen competitive learning network has been developed for the localization and identification of crack.
- ✓ Finally a comparative study has been made between fuzzy logic technique and Kohonen network technique after experimental verification.

1.3. Thesis Layout

The research work has been delineated in this thesis by dividing eight chapters.

Following the Introduction presented in the Chapter 1, the Chapter 2 followed the literature survey which contains the previous studies had been made in the analysis of cracked structure using vibrational techniques, finite element analysis, fuzzy logic techniques, neuro genetic techniques and the application of kohonen network.

Chapter 3 analyses the theoretical expressions obtained for free and forced vibration for computing the localization and identification of crack of a single crack cantilever beam. In this analysis the transverse crack has been taken into consideration.

Chapter 4 defines the concept of the fuzzy logic and outlines the methodology used to design an intelligent fuzzy logic controller to train the data obtain from the theoretical as well as experimental analysis for prediction of relative crack location and relative crack depth. A comparative study has been made between fuzzy logic technique and Kohonen network technique after experimental verification.

Chapter 5 defines the concept of kohonen network. The data obtained from theoretical analysis has been fed to the kohonen competitive learning network. Kohonen network is nothing but a competitive learning network is used here for the detection of crack depth and location. It is processed through a vector quantization algorithm.

Chapter 6 outlines the details of the developed experimental set-up for vibration analysis along with the specifications.

Chapter 7 sketches the results and discussion of the chapters mentioned above.

Chapter 8 highlights the conclusions drawn from the research work and the scope of the future work. The reference taken for the research work and paper published related to the research area has been listed in the last section of the chapter.

CHAPTER 2

LITERTURE SURVEY

CHAPTER 2

Literature Survey

2.1. Introduction

Now a day's crack detection is one of the most important areas of the research. Most of the researchers are doing their research work related to crack detection using various techniques. This chapter highlights the various methodologies uses by researchers in their era of research in the last few decades. The area of research basically includes the theoretical approach, experimental verification and the intelligent techniques.

2.2. Overview

Cracks are a potential source of catastrophic failure in mechanical machines and in civil structures and in aerospace engineering. To avoid the failure caused by cracks, many researchers have performed extensive investigations over the years to develop structural integrity monitoring techniques. Most of the techniques are based on vibration measurement and analysis because, in most cases, vibration based methods can offer an effective and convenient way to detect fatigue cracks in structures. It is always require that structures must safely work during its service life, however damage initiates a breakdown period on the structures. It is unanimous that cracks are among the most encountered damage types in structures. Crack in structures may be hazardous due their dynamic loadings. So crack detection plays an important for structural health monitoring applications.

Many researchers have used the free and forced vibration techniques for developing procedures for crack detection. The eventual goal of this research is to establish new methodologies which will predict the crack location and crack depth in a dynamically vibrating structure with the help of intelligence technique with considerably less computational time and high precision. This chapter recapitulates the previous works, mostly in computational methods for structures, and discusses the possible ways for research.

2.3. Methodologies uses in the area of research on crack detection

Das and Parhi [1] have performed an analytical study on fuzzy inference system for detection of crack location and crack depth of a cracked cantilever beam structure using six input parameters to the fuzzy member ship functions. The six input parameters are percentage deviation of first three natural frequencies and first three mode shapes of the cantilever beam. The two output parameters of the fuzzy inference system are relative crack depth and relative crack location. Experimental setup has been developed for verifying the robustness of the developed fuzzy inference system. The developed fuzzy inference system can predict the location and depth of the crack in a close proximity to the real results. Suresh *et al.* [2] have considered the flexural vibration in a cantilever beam having a transverse surface crack. He has stated that modal frequency parameters are analytically computed for various crack locations and depths using a fracture mechanics based crack model. These computed modal frequencies are used to train a neural network to identify both the crack location and depth presented in this paper. First, the crack location is identified with computed modal frequency parameters. Next, the crack depth is identified with computed modal frequency parameters and the identified crack location.

Pawar *et al.* [3] have performed a composite matrix cracking model, which is implemented in a thin-walled hollow circular cantilever beam using an effective stiffness approach. Using these changes in frequencies due to matrix cracking, a genetic fuzzy system for crack density and crack location detection is generated. The genetic fuzzy system combines the uncertainty representation characteristics of fuzzy logic with the learning ability of genetic algorithm. It is observed that the success rate of the genetic fuzzy system in the presence of noise is dependent on crack density (level of damage). It is found that the genetic fuzzy system shows excellent damage detection and isolation performance, and is robust to presence of noise in data. Das and Parhi [4] have investigated the detection of the cracks in beam structures using the fuzzy Gaussian inference technique. Fuzzy-logic controller here used six input parameters and two output parameters. The input parameters to the fuzzy controller are the relative divergence of the first three natural frequencies and first three mode shapes in dimensionless forms. The output parameters of the fuzzy controller are the relative crack depth and relative crack location in dimensionless forms. The strain-energy release rate has been used for calculating the local stiffnesses of the beam for a mode-I type of the crack. Several boundary conditions are outlined that take into account the crack location. The developed fuzzy controller can predict the location and depth of the crack in close proximity with the real results.

Taghi *et al.* [5] have proposed a method in which damage in a cracked structure was analyzed using genetic algorithm technique. For modeling the cracked-beam structure an analytical model of a cracked cantilever beam was utilized and natural frequencies were obtained through numerical methods. A genetic algorithm is utilized to monitor the possible changes in the natural frequencies of the structure. The identification of the crack location and depth in the cantilever beam was formulated as an optimization problem. Bakhary *et al.* [6] applied Artificial Neural Network for damage detection. In his investigation an ANN model was created by applying Rosenblueth's point estimate method verified by Monte Carlo simulation, the statistics of the stiffness parameters were estimated. The probability of damage existence (PDE) was then calculated based on the probability density function of the existence of undamaged and damaged states. The developed approach was applied to detect simulated damage in a numerical steel portal frame model and also in a laboratory tested concrete slab. The effects of using different severity levels and noise levels on the damage detection results are discussed. Maity and Saha [7] have presented a method called damage assessment in structures from changes in static parameter using neural network. The basic strategy applied in this study was to train a neural network to recognize the behavior of the undamaged structure as well as of the structure with various possible damaged states. When this trained network was subjected to the measured response; it was able to detect any existing damage. The idea was applied on a simple cantilever beam. Strain and displacement were used as possible candidates for damage identification by a back propagation neural network and the superiority of strain over displacement for identification of damage has been observed.

Structural damage detection using neural network with learning rate improvement performed by Fang *et al.* [8] In this study, he has been explore the structural damage detection using frequency response functions (FRFs) as input data to the back-propagation neural network (BPNN).Neural network based damage detection generally consists of a training phase and a recognition phase. Error back-propagation algorithm incorporating gradient method can be applied to train the neural network, whereas the training efficiency heavily depends on the learning rate. While various training algorithms, such as the dynamic steepest descent (DSD) algorithm and the fuzzy steepest descent (FSD) algorithm, have shown promising features (such as improving the learning convergence speed), their performance is hinged upon the proper selection of certain control parameters and control strategy. In this paper, a tunable steepest descent (TSD) algorithm using heuristics approach, which improves the convergence speed significantly without sacrificing the algorithm simplicity and the computational effort, is investigated. The analysis results on a cantilevered beam show that, in all considered damage cases (i.e., trained damage cases and unseen damage cases, single damage cases and multiple-damage cases), the neural network can assess damage conditions with very good accuracy.

Saridakis [9] applied neural networks, genetic algorithms and fuzzy logic for the identification of cracks in shafts by using coupled response measurements. In his research the dynamic behavior of a shaft with two transverse cracks characterized by three measures: position, depth and relative angle. Both cracks were considered to lie along arbitrary angular positions with respect to the longitudinal axis of the shaft and at some distance from the clamped end. A local compliance matrix of two degrees of freedom (bending in both the horizontal and the vertical planes) was used to model each crack. The calculation of the compliance matrix was based on established stress intensity factor expressions and was performed for all rotation angles through a function that incorporated the crack depth and position as parameters. Towards this goal, five different objective functions were proposed and validated; two of these were based on fuzzy logic. More computational intelligence was added through a genetic algorithm, which was used to find the characteristics of the cracks through artificial neural networks that approximate the analytical model. Both the genetic algorithm and the neural networks contributed to a remarkable reduction of the computational time without any significant loss of accuracy. The final results showed that the proposed methodology may constitute an efficient tool for real-time crack identification. An approach for crack detection in beam like structures using RBF (Radial Basis Function) neural network have been performed by Huijian *et al.* [10] with an experimental validation. In the particular research a crack damage detection algorithm was presented using a combination of global and local vibration-based analysis data as input in artificial neural networks (ANNs) for location and severity prediction of crack damage in beam like structures. Finite element analysis has been used to obtain the dynamic characteristics of intact and damaged cantilever steel beams for the first three natural modes. In the experimental analysis, several steel beams with six distributed surface bonded electrical strain gauges and an accelerometer mounted at the tip have been used to obtain modal parameters such as resonant frequencies and strain mode shapes. Finally, the Radial Basis Function ANNs have been trained using the data obtained from the numerical damage case to predicate the severity and localization of the crack damage.

Buezasa *et al.* [11] has been investigating the crack detection in structural elements by means of a generic algorithm optimization method. The present study deals with two and three dimensional models to handle the dynamics of a structural element with a transverse breathing crack. The methodology is not restricted to beam-like structures since it may be applied to any arbitrary shaped 3D element. The crack is simulated as a notch or a wedge with a unilateral Signorini’s contact model. The contact may be partial or total. All the simulations are carried out using the partial differential solver of the general purpose, finite element code FlexPDE. A genetic algorithm (GA) optimization method is successfully employed for the crack detection. The dynamic responses at some points of the damaged structures are compared with the solution of the computational (FE) model using least squares for each proposed crack depth and location. An objective function arises which is then optimized to obtain an estimate of both parameters. Physical experiments were performed with a cantilever damaged beam and the resulting data used as input in the detection algorithm. Panigrahi *et al.* [12] has firstly formulate of an objective function for the genetic search optimization procedure along with the residual force method are presented for the identification of macroscopic structural damage in an uniform strength beam. Two cases have been investigated here. In the first case the width is varied keeping the strength of beam uniform throughout and in the second case both width and depth are varied to represent a special case of uniform strength beam. The developed model requires experimentally determined data as input and detects the location and extent of the damage in the beam. Here, experimental data are simulated numerically by using finite element models of structures with inclusion of random noise on the vibration characteristics. It has been shown that the damage may be identified for the said problems with a good accuracy.

Chou *et al.* [13] stated that, the problem is initially formulated as an optimization problem, which is then solved by using genetic algorithm (GA). Static measurements of displacements at few degrees of freedom (DOFs) are used to identify the changes of the characteristic properties of structural members such as Young's modulus and cross-sectional area, which are indicated by the difference of measured and computed responses. In order to avoid structural analyses in fitness evaluation, the displacements at unmeasured DOFs are also determined by GA. The proposed method is able to detect the approximate location of the damage, even when practical considerations limit the number of on-site measurements to only a few. Suh *et al.* [14] have presented a method to identify the location and depth of a crack on a structure by using hybrid neuro-genetic technique. Feed-forward multi-layer neural networks trained by back-propagation are used to learn the input (the location and depth of a crack)–output (the structural eigen frequencies) relation of the structural system. With this trained neural network, genetic algorithm is used to identify the crack location and depth minimizing the difference from the measured frequencies. The problem of crack identification in a beam when clamp rigidity is unknown performed by Horibe and Asano [15]. The identification method is based on the genetic algorithm (GA) and the proposed method is verified by numerical simulation.

Sahoo and Maity [16] stated that artificial neural networks (ANN) have been proved to be an effective alternative for solving the inverse problems because of the pattern-matching capability. But there is no specific recommendation on suitable design of network for different structures and generally the parameters are selected by trial and error, which restricts the approach context dependent. A hybrid neuro-genetic algorithm is proposed in order to automate the design of neural network for different type of structures. The neural network is trained considering the frequency and strain as input parameter and the location and amount of damage as output parameter. Damage detection methods of structures based on changes in their vibration properties have been widely employed during the last two decades. Existing methods include those based on examination of changes in natural frequencies, mode shapes or mode shape curvatures. Doebling *et al.* [17] published a state-of the- art review on vibration based damage identification methods. Messina *et al.* [18] used the sensitivity and a statistical-based method to structural damage detection. Kosmatka and Ricles [19] presented the modal vibration characterization method using the vibratory residual forces and weighted sensitivity analysis. Ratcliffe [20] performed the frequency and curvature based experiments. Vestroni and Capecchi [21] presented the method for concentrated damage detection based on natural frequency measurement. Gawronski and Sawicki [22] used the method based on modal and sensor norms. Hu *et al.* [23] presented a method using quadratic programming. Law *et al.* [24] presented a method for large-scale structures using super-elements with the concept of damage detection orientation modelling. Sahin and Shenoi [25] have presented a damage detection algorithm using a combination of global and local vibration-based data as input to artificial neural networks (ANNs) for location and severity prediction of the damage.

Sadettin Orhan [26] has been performed an analysis of free and forced vibration of a cracked beam in order to identify the crack in a cantilever. Single- and two-edge cracks were evaluated. The study results suggest that free vibration analysis provides suitable information for the detection of single and two cracks, whereas forced vibration can detect only the single crack condition. However, dynamic response of the forced vibration better describes changes in crack depth and location than the free vibration in which the difference between natural frequencies corresponding to a change in crack depth and location only is a minor effect. Mei *et al.* [27] has been presented his research work on wave vibration analysis of an axially loaded cracked Timoshenko beam. It includes the effects of axial loading, shear deformation and rotary inertia. From wave standpoint, vibrations propagate, reflect and transmit in a structure. The transmission and reflection matrices for various discontinuities on an axially loaded Timoshenko beam are derived. Such discontinuities include cracks, boundaries and changes in section. The matrix relations between the injected waves and externally applied forces and moments are also derived. These matrices are combined to provide a concise and systematic approach to both free and forced vibration analyses of complex axially loaded Timoshenko beams with discontinuities such as cracks and sectional changes. The systematic method is illustrated using several numerical examples.

Viola *et al.* [28] have investigated the changes in the magnitude of natural frequencies and modal response introduced by the presence of a crack on an axially loaded uniform Timoshenko beam using a particular member theory. A new and convenient procedure based on the coupling of dynamic stiffness matrix and line-spring element is introduced to model the cracked beam. The application of the theory is demonstrated by two illustrative examples of bending–torsion coupled beams with different end conditions, for which the influence of axial force, shear deformation and rotatory inertia on the natural frequencies is studied. Moreover, a parametric study to investigate the effect of the crack on the modal characteristics of the beam is conducted. A theoretical and experimental dynamic behavior of different multi-beams systems containing a transverse crack has been presented by Saavedra and Cuitino [29]. The additional flexibility that the crack generates in its vicinity is evaluated using the strain energy density function given by the linear fracture mechanic theory. Based on this flexibility, a new cracked finite element stiffness matrix is deduced, which can be used subsequently in the FEM analysis of crack systems. The proposed element is used to evaluate the dynamic response of a cracked free–free beam and a U-frame when a harmonic force is applied. The resulting parametrically excited system is non-linear and the equations of motion are solved using the Hilbert, Hughes and Taylor integration method implemented using a Matlab software platform.

Kisa and Gurel [30] have investigated the, a novel numerical technique applicable to analyses the free vibration analysis of uniform and stepped cracked beams with circular cross section. In this approach in which the finite element and component mode synthesis methods are used together, the beam is detached into parts from the crack section. These substructures are joined by using the flexibility matrices taking into account the interaction forces derived by virtue of fracture mechanics theory as the inverse of the compliance matrix found with the appropriate stress intensity factors and strain energy release rate expressions. To reveal the accuracy and effectiveness of the offered method, a number of numerical examples are given for free vibration analysis of beams with transverse non-propagating open cracks. Numerical results showing good agreement with the results of other available studies, address the effects of the location and depth of the cracks on the natural frequencies and mode shapes of the cracked beams.

An identification procedure to determine the crack characteristics (location and size of the crack) from dynamic measurements has been developed and tested by Shen and Taylor [31]. This procedure is based on minimization of either the “mean-square” or the “max” measure of difference between measurement data (natural frequencies and mode shapes) and the corresponding predictions obtained from the computational model. Necessary conditions are obtained for both formulations. The method is tested for simulated damage in the form of one-side or symmetric cracks in a simply supported Bernoulli-Euler beam. The sensitivity of the solution of damage identification to the values of parameters that characterize damage is discussed. Crack detection in beam-like structures has been presented by Rosales *et al.* [32]. Two approaches are herein presented: The solution of the inverse problem with a power series technique (PST) and the use of artificial neural networks (ANNs). Cracks in a cantilever Bernoulli Euler (BE) beam and a rotating beam are detected by means of an algorithm that solves the governing vibration problem of the beam with the PST. The ANNs technique does not need a previous model, but a training set of data is required. It is applied to the crack detection in the cantilever beam with a transverse crack. The first methodology is very simple and straightforward, though no optimization is included. It yields relative small errors in both the location and depth detection. When using one network for the detection of the two parameters, the ANNs behave adequately.

However better results are found when one ANN is used for each parameter. Finally, a combination between the two techniques is suggested.

Gounaris and Dimarogonas [33] performed a finite element of a cracked prismatic beam for structural analysis. A surface crack on a beam section introduces a local flexibility to the structural member. In order to model the structure for FEM analysis, a finite element for the cracked prismatic beam is developed. Strain energy concentration arguments lead to the development of a compliance matrix for the behavior of the beam in the vicinity of the crack. This matrix is used to develop the stiffness matrix for the cracked beam element and the consistent mass matrix. The element developed can be used in any appropriate matrix analysis of structures program. The element was used to evaluate the dynamic response of a cracked cantilever beam to harmonic point force excitation. Resonant frequencies and vibration amplitudes are considerably affected by the existence of moderate cracks.

Onard *et al.* [34] has been presented free-vibration behavior of a cracked cantilever beam and crack detection .This study is based on cracks that occurred in metal beams obtained under controlled fatigue-crack propagation. The beams were clamped in a heavy vise and struck in order to obtain a clean impulse modal response. Spectrograms of the free-decay responses showed a time drift of the frequency and damping: the usual hypothesis of constant modal parameters is no longer appropriate, since the latter are revealed to be a function of the amplitude. Signal processing such as the worm transform and phase spectrogram methods have been developed with enough accuracy to display the behavior of an uncracked beam where a slight non-linear stiffness is generated by the clamping. Moreover, extracted worms show that the second mode of a beam with a deep crack is modulated in frequency by the "first mode. In fact, the dominant mode opens and closes the crack, thereby modulating the beam stiffness, which affects higher modal frequencies. With deep cracks, three vibration states are observed: one where the crack is alternately fully open and fully closed, a second with a crack partially opened, and a third with alternating force acting on a closed crack. In the latter case, the peak force is smaller than the intrinsic closure load of the crack. The "first state is difficult for a small crack to reach since high-amplitude excitation is required to fully open the crack. For crack detection purposes, the damping criterion, harmonic distortion criterion and bispectrum appear less sensitive to small cracks than the phase spectrogram and coherent-modulated power.

Detection of the Crack in Cantilever Structures Using Fuzzy Gaussian Inference Technique has been introduced by Das and Parhi [35]. Detection of the cracks in beam structures using the fuzzy Gaussian inference technique has been investigated by Das and Parhi. Fuzzy-logic controller here used six input parameters and two output parameters. The input parameters to the fuzzy controller are the relative divergence of the first three natural frequencies and first three mode shapes in dimensionless forms. The output parameters of the fuzzy controller are the relative crack depth and relative crack location in dimensionless forms. The strain-energy release rate has been used for calculating the local stiffness of the beam for a mode-I type of the crack. Several boundary conditions are outlined that take into account the crack location. The developed fuzzy controller can predict the location and depth of the crack in close proximity with the real results. Chandrasekhar *et al.* [36] has stated that geometric and measurement uncertainty cause considerable problem in damage assessment which can be alleviated by using a fuzzy logic-based approach for damage detection. Curvature damage factor (CDF) of a tapered cantilever beam is used as damage indicators. Monte Carlo simulation (MCS) is used to study the changes in the damage indicator due to uncertainty in the geometric properties of the beam. Variation in these CDF measures due to randomness in structural parameter, further contaminated with measurement noise, are used for developing and testing a fuzzy logic system (FLS). Results show that the method correctly identifies both single and multiple damages in the structure.

Das and Parhi [37] applied hybrid artificial intelligence technique for fault detection in a cracked cantilever beam. The hybrid technique used here uses a fuzzy-neuro controller. Here the fuzzy-neuro controller has two parts. The first part is comprised of the fuzzy controller, and the second part is comprised of the neural controller. The input parameters of the neural segment of the fuzzy-neuro controller are relative deviation of the first three natural frequencies and relative values of percentage deviation for the first three mode shapes, along with the initial outputs of the fuzzy controller. The output parameters of the fuzzy-neuro controller are final relative crack depth and final relative crack location. The results of the developed fuzzy-neuro controller and experimental method are in good agreement. Hasanzadeh *et al.* [38] have been proposed an aligning method, which is formalized by a fuzzy recursive least square algorithm as a learning methodology for electromagnetic alternative current field measurement (ACFM) probe signals of a crack. This method along with a set of fuzzy linguistic rules, including adequate adaptation of different crack shapes for combining knowledge and data whenever the superposition theory can be utilized, provides a means to compensate for the lack of sufficient samples in available crack databases. Salahshoor *et al.* [39] has been described that the issue of fault detection and diagnosis has gained widespread industrial interest in process condition monitoring applications. They have presented an innovative data-driven fault detection and diagnosis methodology on the basis of a distributed configuration of three adaptive neuro-fuzzy inference system (ANFIS) classifiers for an industrial 440 MW power plant steam turbine with once-through Benson type boiler. Each ANFIS classifier has been developed for a dedicated category of four steam turbine faults. They have also conducted experimental studies to realize such fault categorization scheme.

Kohonen *et al.* [40] have been proposed that the Self Organizing Map (SOM) method is a new powerful software tool for the visualization of high dimensional data. They explain that SOM converts complex, no-linear statistical relationship between high dimensional data into simple geometric relationship on a two-dimensional display. It may also be thought to produce some kind of abstraction. These two aspects visualization and abstraction occur in a member of complex engineering task such as process analysis, machine perception, control and communication. Cottrel *et al.* [41] have been performed an analytical study on Kohonen Network and suggested that the Kohonen algorithm is a powerful tool for data analysis. In that case they define a specific algorithm which provides a simultaneous classification of the observation and of the modalities. Vesanto *et al.* [42] have been proposed that the Self-Organizing Map (SOM) is a vector quantization method which places the prototype vectors on a regular low-dimensional grid in an ordered fashion. This makes the SOM a powerful visualization tool. Also its performance in terms of computational load is evaluated and compared to a corresponding C program. Kauppinen *et al.* [43] have been proposed a non-segmenting defect detection technique combined with a self-organizing map (SOM) based classifier and user interface. They have tried to avoid the problems with adaptive detection techniques, and to provide an intuitive user interface for classification, helping in training material collection and labeling, and with a possibility of easily adjusting the class boundaries. The approach is illustrated with examples from wood surface inspection. Many researchers have been used this kohonen network in different area of research but in this paper we have proposed the essential processes as well as the mechanism followed in the Kohonen Network for the detection of crack depth and crack location.

Hasanzadeh *et al.* [44] have developed a methodology for sizing of surface cracks by AC field measurement technique. They have developed an aligning method is formalized by a fuzzy recursive least square algorithm as a learning methodology for electromagnetic alternative current field measurement (ACFM) probe signals of a crack (data). This method along with a set of fuzzy linguistic rules, including adequate adaptation of different crack shapes (knowledge) for combining knowledge and data whenever the superposition theory can be utilized, provide a means to compensate for the lack of sufficient samples in available crack databases. Buezas *et al.* [45] have presented a technique for damage detection in structural element using genetic algorithm optimization method with the consideration of a crack contact model. In this technique the crack is simulated as a notch or a wedge with a unilateral Signorini contact model. The contact can be partial or total. All the simulations are carried out using the general purpose partial differential solver FlexPDE, a finite element (FE) code. A genetic algorithm (GA) optimization method is successfully employed for the crack detection. The dynamic responses at some points of the damaged structures are compared with the solution of the computational (FE) model using least squares for each proposed crack depth and location. An objective function arises which is then optimized to obtain the parameters. The method is developed for bi- and three-dimensional models to handle the dynamics of a structural element with a transverse breathing crack. Nobahari and Seyedpoor [46] have developed a technique for Structural damage detection using an efficient correlation-based index and a modified genetic algorithm; they have developed an efficient optimization procedure to detect multiple damage in structural systems. Natural frequency changes of a structure are considered as a criterion for damage presence. In order to evaluate the required natural frequencies, a finite element analysis (FEA) is utilized. A modified genetic algorithm (MGA) with two new operators (health and simulator operators) is presented to accurately detect the locations and extent of the eventual damage. An efficient correlation-based index (ECBI) as the objective function for the optimization algorithm is also introduced.

A method for Structural damage detection using fuzzy cognitive maps (FCM) and Hebian learning techniques have been developed by Beena and Ganguli [47]. In their analysis a Structural damage is modeled using the continuum mechanics approach as a loss of stiffness at the damaged location. A finite element model of a cantilever beam is used to calculate the change in the first six beam frequencies because of structural damage. The measurement deviations due to damage are fuzzified and then mapped to a set of faults using FCM. The input concepts for the FCM are the frequency deviations and the output of the FCM is at five possible damage locations along the beam. The FCM works quite well for structural damage detection for ideal and noisy data. Further improvement in performance is obtained when an unsupervised neural network approach based on Hebbian learning is used to evolve the FCM. Liu *et al.* [48] have stated a methodology for structural damage diagnosis using neural network and feature fusion. In their analysis a structure damage diagnosis method combining the wavelet packet decomposition, multi-sensor feature fusion theory and neural network pattern classification was presented. Firstly, vibration signals gathered from sensors were decomposed using orthogonal wavelet. Secondly, the relative energy of decomposed frequency band was calculated. Thirdly, the input feature vectors of neural network classifier were built by fusing wavelet packet relative energy distribution of these sensors. Finally, with the trained classifier, damage diagnosis and assessment was realized. The result indicates that, a much more precise and reliable diagnosis information is obtained and the diagnosis accuracy is improved as well.

CHAPTER 3

THEORETICAL VIBRATION ANALYSIS FOR IDENTIFICATION OF CRACK

CHAPTER 3 Theoretical Vibration Analysis for Identification of Crack

3.1. Introduction

In this present research work it has been analyzed that the crack can be detected in the various structures through visual inspection or by the method of measuring natural frequency, mode shape and structural damping. As the measurement of natural frequency and mode shape is quite easy as compared to other parameters, so in this chapter a logical approach has been adopted to develop the expression to calculate the natural frequency and the mode shape of the cantilever beam with the presence of a transverse crack and the effect of natural frequency in the presence of crack. Experimental analysis has been done over cracked cantilever beam specimen for validation of the theory established.

3.2. Local flexibility of a cracked cantilever beam under axial load and bending moment

A cantilever beam with a transverse surface crack of depth ‘a_1’ on beam of width ‘B’ and height ‘W’ is considered for the current research. The beam is subjected to axial force (P_1) and bending moment (P_2) (Fig.3.1) which gives coupling with the longitudinal and transverse motion. The presence of crack introduces a local flexibility, which can be defined in matrix form, the dimension of which depends on the degrees of freedom. Here a 2x2 matrix is considered.

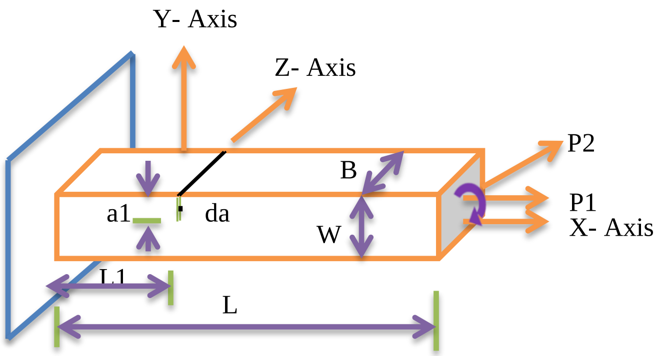


Figure: 3.1 Geometry of Cracked Cantilever Beam

The strain energy release rate at the fractured section can be written as (Tada *et al.* [49])

$$J = \frac{1}{E'}(K_{I1} + K_{I2})^2, \text{ Where } \frac{1}{E'} = \frac{1-v^2}{E'} \text{ (for plane strain condition);} \quad (3.1a)$$

$$= \frac{1}{E}\text{(for plane stress condition)} \quad (3.1b)$$

K_{I1}, K_{I2} are the stress intensity factors of mode I (opening of the crack) for load P_1 and P_2 respectively. The values of stress intensity factors from earlier studies are;

$$K_{I1} = \frac{P_1}{BW}\sqrt{\pi a}(F_1(\frac{a}{W})), K_{I2} = \frac{6P_2}{BW^2}\sqrt{\pi a}\,(F_2(\frac{a}{W})) \quad (3.2)$$

Where expressions for F_1 and F_2 are as follows

$$F_1(\frac{a}{W}), = (\frac{2W}{\pi a}\tan(\frac{\pi a}{2W}))^{0.5}\left\{\frac{0.752 + 2.02(a/W) + 0.37(1-\sin(\pi a/2W))^3}{\cos(\pi a/2W)}\right\} \quad (3.3)$$

$$F_2(\frac{a}{W}), = (\frac{2W}{\pi a}\tan(\frac{\pi a}{2W}))^{0.5}\left\{\frac{0.923 + 0.199(1-\sin(\pi a/2W))^4}{\cos(\pi a/2W)}\right\}$$

Let U_t be the strain energy due to the crack. Then from Castigliano's theorem, the additional displacement along the force P_i is:

$$u_i = \frac{\partial U_t}{\partial P_i} \quad (3.4)$$

The strain energy will have the form, $U_t = \int_0^{a_1} \frac{\partial U_t}{\partial a} da = \int_0^{a_1} J\, da$ (3.5)

Where J= $\frac{\partial U_t}{\partial a}$ the strain energy density function.

From (Equations 3.4 and 3.5), we will get

$$u_i = \frac{\partial}{\partial P_i}\left[\int_0^{a_1} J(a)\, da\right] \quad (3.6)$$

The flexibility influence co-efficient C_{ij} will be, by definition

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_0^{a_1} J(a)\, da \quad (3.7)$$

To find out the final flexibility matrix we have to integrate over the breadth 'B'

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j} \int_{-B/2}^{+B/2} \int_0^{a_1} J(a)\, da\, dz \tag{3.8}$$

Taking the value of strain energy release rate from the Equation (3.1a), the equation (3.8) can be modifies as

$$C_{ij} = \frac{B}{E'} \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{a_1} (K_{I1} + K_{I2})^2\, da \tag{3.9}$$

Putting $\xi = (a/w), d\xi = \dfrac{da}{W}$

We get da = W $d\xi$ and when a = 0, $\xi = 0$; $a = a_1$, $\xi = a_1/W = \xi_1$

Putting the above condition in Equation (3.9) we will get

$$C_{ij} = \frac{BW}{E'} \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{\xi_1} (K_{I1} + K_{I2})^2\, d\xi \tag{3.10}$$

From the Equation (3.10), calculating C_{11}, C_{12} (=C_{21}) and C_{22} we get,

$$C_{11} = \frac{BW}{E'} \int_0^{\xi_1} \frac{\pi a}{B^2 W^2} 2(F_1(\xi))^2\, d\xi \;= \frac{2\pi}{BE'} \int_0^{\xi_1} \xi (F_1(\xi))^2\, d\xi \tag{3.11}$$

$$C_{12} = C_{21} = \frac{12\pi}{E'BW} \int_0^{\xi_1} \xi F_1(\xi) F_2(\xi)\, d\xi \tag{3.12}$$

$$C_{22} = \frac{72\pi}{E'BW^2} \int_0^{\xi_1} \xi F_2(\xi) F_2(\xi)\, d\xi \tag{3.13}$$

Converting the influence co-efficient into dimensionless form, we will get the final expression as

$$\overline{C_{11}} = C_{11} \frac{BE'}{2\pi} \quad \overline{C_{12}} = C_{12} \frac{E'BW}{12\pi} = \overline{C_{21}}\ ;\ \overline{C_{22}} = C_{22} \frac{E'BW^2}{72\pi} \tag{3.14}$$

The local stiffness matrix can be obtained by taking the inversion of compliance matrix. i.e.

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^{-1} \quad (3.15)$$

3.3. Analysis of Vibration Characteristics of a Cracked Cantilever Beam

3.3.1. Analysis of Free Vibration

A cantilever beam of length ‘L’ width ‘B’ and depth ‘W’, with a crack of depth ‘a_1’ at a distance ‘L_1’ from the fixed end is considered (Fig. 3.1). Taking $u_1(x,t)$ and $u_2(x,t)$ as the amplitudes of longitudinal vibration for the sections before and after the crack and $y_1(x,t)$, $y_2(x,t)$ are the amplitudes of bending vibration for the same sections (Fig. 3.2).

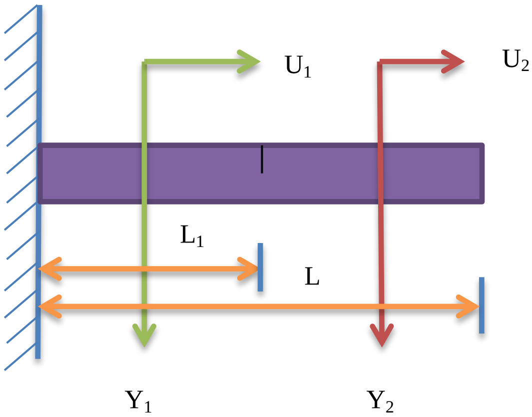


Figure: 3.2 Beam Model

The normal function for the system can be defined as

$$\bar{u}_1(\bar{x}) = A_1 \cos(\bar{K}_u \bar{x}) + A_2 \sin(\bar{K}_u \bar{x}) \quad (3.16a)$$

$$\bar{u}_2(\bar{x}) = A_3 \cos(\bar{K}_u \bar{x}) + A_4 \sin(\bar{K}_u \bar{x}) \quad (3.16b)$$

$$\bar{y}_1(\bar{x}) = A_5 \cosh(\bar{K}_y \bar{x}) + A_6 \sinh(\bar{K}_y \bar{x}) + A_7 \cos(\bar{K}_y \bar{x}) + A_8 \sin(\bar{K}_y \bar{x}) \quad (3.16c)$$

$$\bar{y}_2(\bar{x}) = A_9 \cosh(\bar{K}_y \bar{x}) + A_{10} \sinh(\bar{K}_y \bar{x}) + A_{11} \cos(\bar{K}_y \bar{x}) + A_{12} \sin(\bar{K}_y \bar{x}) \quad (3.16d)$$

Where $\bar{x} = \frac{x}{L}, \bar{u} = \frac{u}{L}, \bar{y} = \frac{y}{L}, \beta = \frac{L_1}{L}$

$$\bar{K}_u = \frac{\omega L}{C_u}, C_u = \left(\frac{E}{\rho}\right)^{1/2}, \bar{K}_y = \left(\frac{\omega L^2}{C_y}\right)^{1/2}, C_y = \left(\frac{EI}{\mu}\right)^{1/2}, \mu = A\rho$$

A_i, (i=1, 12) Constants are to be determined, from boundary conditions. The boundary conditions of the cantilever beam in consideration are:

$$\bar{u}_1(0)=0\,; \tag{3.17a}$$

$$\bar{y}_1(0)=0\,; \tag{3.17b}$$

$$\bar{y}_1'(0)=0\,; \tag{3.17c}$$

$$\bar{u}_2'(1)=0\,; \tag{3.17d}$$

$$\bar{y}''_2(1)=0\,; \tag{3.17e}$$

$$\bar{y}_2'''(1)=0\,; \tag{3.17f}$$

At the cracked section:

$$\bar{u}'_1(\beta)=\bar{u}'_2(\beta)\,; \tag{3.18a}$$

$$\bar{y}_1(\beta)=\bar{y}_2(\beta)\,; \tag{3.18b}$$

$$\bar{y}_1''(\beta)=\bar{y}_2''(\beta)\,; \tag{3.18c}$$

$$\bar{y}_1'''(\beta)=\bar{y}_2'''(\beta) \tag{3.18d}$$

Also at the cracked section (due to the discontinuity of axial deformation to the left and right of the crack), we have:

$$AE\frac{du_1(L_1)}{dx}=K_{11}(u_2(L_1)-u_1(L_1))+K_{12}\left(\frac{dy_2(L_1)}{dx}-\frac{dy_1(L_1)}{dx}\right) \tag{3.19}$$

Multiplying both sides of the above equation by $\frac{AE}{LK_{11}K_{12}}$ we will get;

$$M_1M_2\bar{u}'(\beta)=M_2(\bar{u}_2(\beta)-\bar{u}_1(\beta))+M_1(\bar{y}_2'(\beta)-\bar{y}_1'(\beta)) \tag{3.20}$$

Similarly at the crack section (due to the discontinuity of slope to the left and right of the crack)

$$EI\frac{d^2y_1(L_1)}{dx^2}=K_{21}(u_2(L_1)-u_1(L_1))+K_{22}\left(\frac{dy_2(L_1)}{dx}-\frac{dy_1(L_1)}{dx}\right) \tag{3.21}$$

Multiplying both sides of the above equation by $\dfrac{EI}{L^2 K_{22} K_{21}}$ we will get,

$$M_3 M_4 \bar{y}_1''(\beta) = M_3(\bar{u}_2(\beta) - \bar{u}_1(\beta)) + M_4(\bar{y}_2'(\beta) - \bar{y}_1'(\beta)) \quad (3.22)$$

Where, $M_1 = \dfrac{AE}{LK_{11}}$, $M_2 = \dfrac{AE}{K_{12}}$, $M_3 = \dfrac{EI}{LK_{22}}$, $M_4 = \dfrac{EI}{L^2 K_{21}}$

The normal functions as stated in Equation (3.16) along with the boundary conditions as mentioned above equations (3.17) and (3.18) yield the characteristic equation of the system as: $|Q| = 0$ (3.23)

This determinant is a function of natural circular frequency (ω), the relative location of the crack (β) and the local stiffness matrix (K) which in turn is a function of the relative crack depth (a1/W).

3.3.2. Analysis of Forced Analysis

If the cantilever beam with transverse crack is excited at its free end by a harmonic excitation ($Y = Y_0 \sin(\omega t)$), the non-dimensional amplitude at the free end may be expressed as $\bar{y}_2(1) = \dfrac{y_0}{L} = \bar{y}_0$. Therefore the boundary conditions for the beam remain same as before except the boundary condition $\bar{y}_2'''(1) = 0$ which modified as $\bar{y}_2(1) = \bar{y}_0$. The constants A_i, i=1, to 12 are then computed from the algebraic condition

$$Q_1 D = B_1 \quad (3.24)$$

Q_1 is the (12 x 12) matrix obtained from boundary conditions as mentioned above,

D is a column matrix obtained from the constants,

B_1 is a column matrix, transpose of which is given by, $B_1^T = [0\,0\,0\,\bar{y}_0\,0\,0\,0\,0\,0\,0\,0\,0]$ (3.25)

3.4. Finite Element Formulation

3.4.1. Theory

The beam with a transverse edge crack is clamped at left end, free at right end and has uniform structure with a constant rectangular cross-section of 800 mm X 38 mm X 6 mm. The Euler-Bernoulli beam model is assumed for the finite element formulation. The crack in this particular case is assumed to be an open crack and the damping is not being considered in this theory. Both single and double edged crack are considered for the formulation.

3.4.2. Governing Equations

The free bending vibration of an Euler-Bernoulli beam of a constant rectangular cross section is given by the following differential equation as given in:

$$EI\frac{d^4y}{dx^4} - m\omega_i^2 y = 0 \tag{3.26}$$

Where 'm' is the mass of the beam per unit length (kg/m), 'ω_i' is the natural frequency of the ith mode (rad/sec), E is the modulus of elasticity (N/m^2) and I is the moment of inertia (m^4). By defining $\lambda^4 = \frac{m\omega_i^2}{EI}$ equation is rearranged as a fourth-order differential equation as follows: $\frac{d^4y}{dx^4} - \lambda^4 y = 0$ (3.27)

The general solution to equation is

$$y = A\cos\lambda_i x + B\sin\lambda_i x + C\cosh\lambda_i x + D\sinh\lambda_i x \tag{3.28}$$

Where A, B, C, D are constants and 'λi' is a frequency parameter. Adopting Hermitian shape functions, the stiffness matrix of the two-noded beam element without a crack is obtained using the standard integration based on the variation in flexural rigidity.

The element stiffness matrix of the un cracked beam is given as

$$\lfloor K^e \rfloor = \int [B(x)]^T EI[B(x)]dx \tag{3.29}$$

$$[B(x)] = \{H_1(x)H_2(x)H_3(x)H_4(x)\} \tag{3.30}$$

Where $[H_1(x), H_2(x), H_3(x), H_4(x)]$ is the Hermitian shape functions defined as

$$H_1(x) = 1 - \frac{3x^2}{l^2} + \frac{2x^3}{l^3}, H_2(x) = x - \frac{2x^2}{l} + \frac{x^3}{l^2}$$

$$H_3(x) = \frac{3x^2}{l^2} - \frac{2x^3}{l^3}, \ H_4(x) = -\frac{x^2}{l} + \frac{x^3}{l^2} \tag{3.31}$$

Assuming the beam rigidity EI is constant and is given by EI_0 within the element, and then the element stiffness is

$$[K^e] = \frac{EI_0}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix} \tag{3.32}$$

$$[K_c^e] = [K^e] - [K_c] \tag{3.33}$$

Here, $\left[K_c^e\right] =$ Stiffness matrix of the cracked element, $\left[K^e\right] =$ Element stiffness matrix, $\left[K_c\right] =$ Reduction in stiffness matrix due to the crack.

According to (Peng *et al.* [50]), the matrix [Kc] is

$$[K_c] = \begin{bmatrix} K_{11} & K_{12} & -K_{11} & K_{14} \\ K_{12} & K_{22} & -K_{12} & K_{24} \\ -K_{11} & -K_{12} & K_{11} & -K_{14} \\ K_{14} & K_{24} & -K_{14} & K_{44} \end{bmatrix} \tag{3.34}$$

Where, $K_{11} = \frac{12E(I_0 - I_c)}{L^4}\left[\frac{2l_c^3}{L^2} + 3l_c\left(\frac{2L_1}{L^2} - 1\right)^2\right]$

$$K_{14} = \frac{12E(I_0 - I_c)}{L^3}\left[\frac{l_c^3}{L^2} + l_c\left(2 - \frac{5L_1}{L} + \frac{6L_1^2}{L^2}\right)^2\right]$$

$$K_{12} = \frac{12E(I_0 - I_c)}{L^3}\left[\frac{l_c^3}{L^2} + l_c\left(2 - \frac{7L_1}{L} + \frac{6L_1^2}{L^2}\right)^2\right]$$

$$K_{24} = \frac{12E(I_0 - I_c)}{L^2}\left[\frac{3l_c^3}{L^2} + 2l_c\left(2 - \frac{9L_1}{L} + \frac{9L_1^2}{L^2}\right)^2\right]$$

$$K_{22} = \frac{12E(I_0 - I_c)}{L^3}\left[\frac{3l_c^3}{L^2} + 2l_c\left(\frac{3L_1}{L} - 2\right)^2\right], \quad K_{44} = \frac{12E(I_0 - I_c)}{L^2}\left[\frac{3l_c^3}{L^2} + 2l_c\left(\frac{3L_1}{L} - 1\right)\right]$$

Here, lc=1.5W, L=Total length of the beam, L_1=Distance between the left node and crack

$I_0 = \frac{BW^3}{12} =$ Moment of inertia of the beam cross section, $Ic = \frac{B(W-a)^3}{12} =$ Moment of inertia of the beam with crack.

It is supposed that the crack does not affect the mass distribution of the beam. Therefore, the consistent mass matrix of the beam element can be formulated directly as

$$\left[M^e\right] = \int_0^1 \rho A[H(x)]^T [H(x)]dx \tag{3.35}$$

$$\left[M^e\right] = \frac{\rho A l}{420}\begin{bmatrix} 156 & 22l & 54 & -13l \\ 22l & 4l^2 & 13l & -3l^2 \\ 54 & 13l & 156 & -22l \\ -13l & -3l^2 & -22l & 4l^2 \end{bmatrix} \tag{3.36}$$

The natural frequency then can be calculated from the relation.

$$[-\omega^2[M] + [K]]\{q\} = 0 \tag{3.37}$$

Where,

q=displacement vector of the beam

3.4.3. Process of Crack Detection

Detection of crack in a cantilever beam has been performed in two methods. First the finite element model of the cracked cantilever beam is developed and the beam is discretized into a number of elements, and the crack position is assumed to be in each of the elements. Next, for each position of the crack in each element, depth of the crack is varied. Modal analysis for each position and depth is then performed to determine the natural frequencies of the beam.

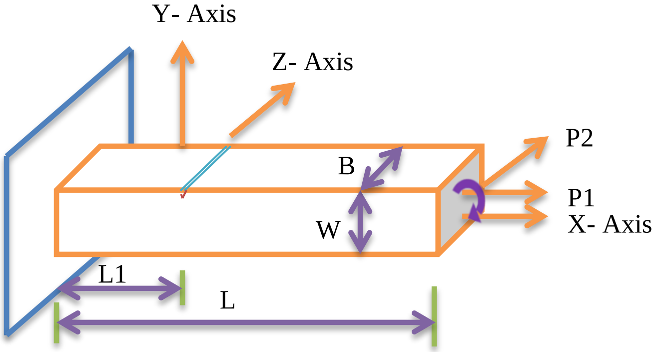


Figure: 3.3 Representation of a Single Crack Cantilever Beam

CHAPTER 4

ANALYSIS OF FUZZY INFERENCE SYSTEM FOR IDENTIFICATION OF CRACK

CHAPTER 4

Analysis of Fuzzy Inference System for Identification of Crack

4.1. Introduction

In order to develop a reliable, efficient and economical approach to increase the safety and reduce the maintenance cost of elastic structures, many researchers have been developed various structural health monitoring techniques. Although improved design methodologies have significantly enhanced the reliability and safety of structures, it is still not possible to build a structure that has zero percent probability of failure. In the recent years, researchers have motivated to words the development of intelligent techniques for the fault detection. This current research presents methodologies for structural damage detection and assessment using fuzzy interface system. In this chapter an intelligent controller has been projected for localization and identification of crack.

Fuzzy sets originated in the year 1965 and this concept was proposed by Lofti A. Zadeh. Since then it has grown and is found in several application areas. According to Zadeh, The notion of a fuzzy set provides a convenient point of departure for the construction of a conceptual framework which parallels in many respects of the framework used in the case of ordinary sets, but is more general than the latter and potentially, may prove to have a much wider scope of applicability, specifically in the fields of pattern classification and information processing.” Fuzzy logics are multi-valued logics that form a suitable basis for logical systems reasoning under uncertainty or vagueness that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. These evaluations can be formulated mathematically and processed by computers, in order to apply a more human-like way of thinking in the programming of computers. Fuzzy logic provides an inference morphology that enables approximate human reasoning capabilities to be applied to knowledge-based systems. The theory of fuzzy logic provides a mathematical strength to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. Fuzzy systems are suitable for uncertain or approximate reasoning, especially for the system with a mathematical model that is difficult to derive. Fuzzy logic allows decision making with estimated values under incomplete or uncertain information.

4.2. Fuzzy Sets and Membership Functions

The concept of a fuzzy set is an extension of the concept of a crisp set. Similar to a crisp set a universe set U is defined by its membership function from U to [0, 1]. Consider U to be a non-empty set also known as the universal set or universe of discourse or domain. A fuzzy set on U is defined as $\mu_A(x): U \to [0,1]$. Here μ_A is known as the membership function, and $\mu_A(x)$ is known as the membership grade of x. Membership function is the degree of truth or degree of compatibility. The membership function is the crucial component of a fuzzy set. Therefore all the operations on fuzzy sets are defined based on their membership functions.

The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. There are different membership functions associated with each input and output response. Reasonable functions are often piecewise linear function, such as triangular or trapezoidal functions. The value for the membership function can be taken in the interval [0, 1]. When the functions are nonlinear the Gaussian membership function will be taken for the smooth operation.

4.3. Fuzzy Inference System

A fuzzy inference system is the process of formulating the mapping from a given input to an output using fuzzy logic. To compute the output of this FIS for the given the inputs, we must go through six steps:

- ✓ Determining a set of fuzzy rules.
- ✓ Fuzzifying the inputs using the input membership functions.
- ✓ Combining the fuzzified inputs according to the fuzzy rules to establish rule strength.
- ✓ Finding the consequence of the rule by combining the rule strength and the output membership function.
- ✓ Combining the consequences to get an output distribution, and
- ✓ Defuzzifying the output distribution.

Fuzzy inference systems have been successfully applied in fields such as automatic control, fault diagnosis, data classification, decision analysis, expert systems, and computer vision.

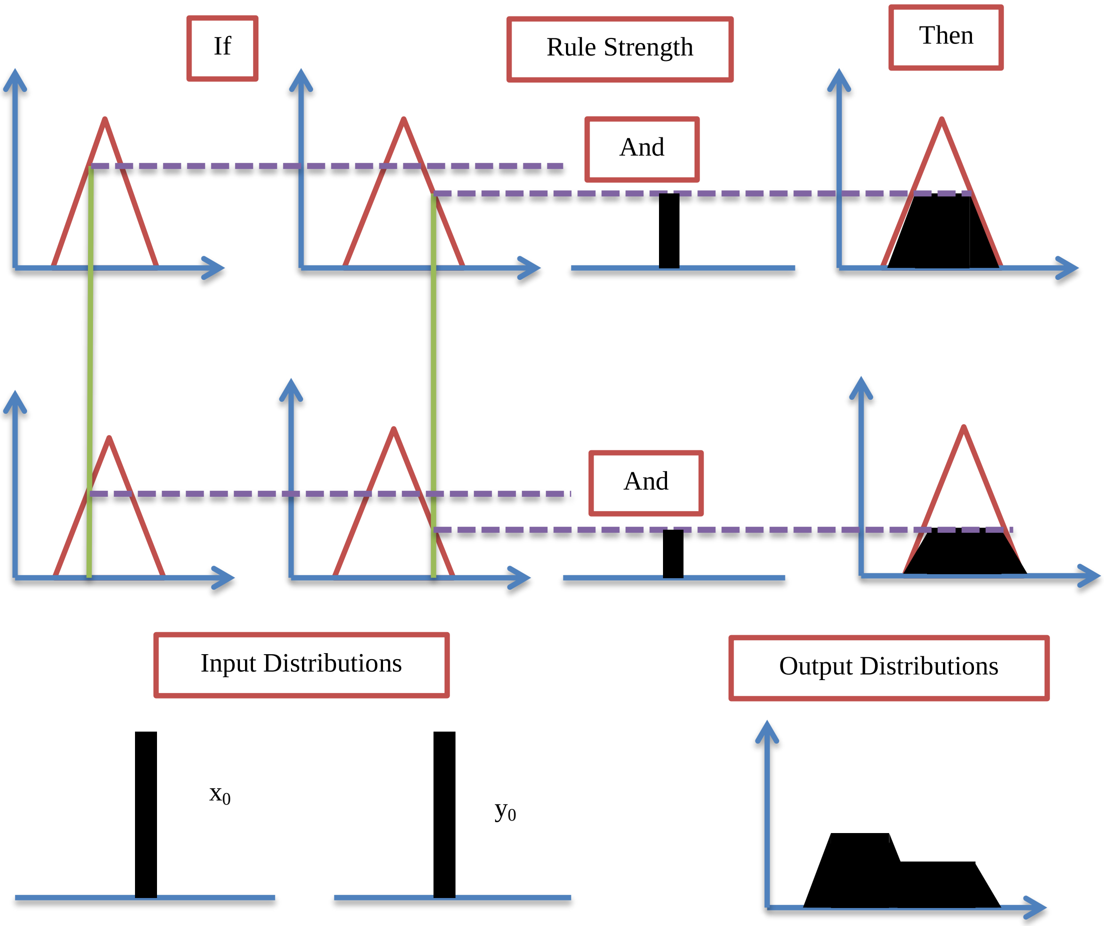


Figure: 4.1 Schematic Diagram of Operation of a Fuzzy Interface System

4.3.1.Fuzzy Linguistic Variables

Just like an algebraic variable takes numbers as values, a linguistic variable takes words or sentences as values. The set of values that it can take is called its term set. Each value in the term set is a fuzzy variable defined over a base variable. The base variable defines the universe of discourse for all the fuzzy variables in short. In short the hierarchy is as follows: Linguistic variable → Fuzzy variable → Base variable.

In 1973, Professor Lotfi Zadeh [51] proposed the concept of linguistic or "fuzzy" variables. Think of them as linguistic objects or words, rather than numbers. Suppose that X = "age." Then we can define fuzzy sets "young," "middle aged," and "old" that are characterized by MFs $\mu_{young}(x), \mu_{middleaged}(x)$, and $\mu_{old}(x)$, respectively. Just as a variable can assume various values, a linguistic variable "Age" can assume different linguistic values, such as "young," "middle aged "and" old" in this case. If "age" assumes the value of "young," then we have the expression "age is young," and so forth for the other values.

4.3.2. Fuzzy Controller/ Fuzzy If-Then Rule

Fuzzy logic controllers are based on the combination of Fuzzy set theory and fuzzy logic. Systems are controlled by fuzzy logic controllers based on rules instead of equations. This collection of rules is known as the rule base usually in the form of IF-THEN-ELSE statements. Here the IF part is known as the antecedent and the THEN part is the consequent. The antecedents are connected with simple Boolean functions like AND, OR, NOT etc., Figure 4.2 outlines a simple architecture for a fuzzy logic controller [52]. The outputs from a system are converted into a suitable form by the fuzzification block. Once all the rules have been defined based on the application, the control process starts with the computation of the rule consequences. The computation of the rule consequences takes place within the computational unit. Finally, the fuzzy set is defuzzified into one crisp control action using the defuzzification module.

A fuzzy if-then rule (also known as fuzzy rule, fuzzy implication or fuzzy conditional statement) assumes the form "if x is A then y is B". Where A and B are linguistic values defined by fuzzy sets on universes of discourse x and y respectively. Often "x is A" is called the antecedent or premise, while "y is B" is called the consequence or conclusion. (Some of the linguistic terms used are shown in Table: 4.1).

4.3.3. Creating Fuzzy Rules

Fuzzy rules are a collection of linguistic statements that describe how the FIS should make a decision regarding classifying an input or controlling an output. Fuzzy rules are always written in the following form:

if (input1 is membership function1) and/or (input2 is membership function2) and/or …. then ($output_n$ is output membership $function_n$).

For example: one could make up a rule that says: if temperature is high and humidity is high then room is hot.

There would have to be membership functions that define what we mean by high temperature (input1), high humidity (input2) and a hot room (output1). This process of taking an input such as temperature and processing it through a membership function to determine what we mean by "high" temperature is called fuzzification. Also, we must define what we mean by "and" / "or" in the fuzzy rule. This is called fuzzy combination.

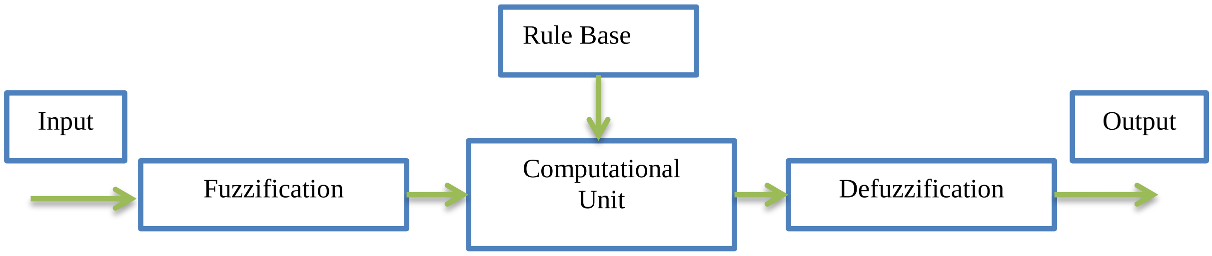


Figure: 4.2 Fuzzy Controller Architecture

4.3.4. Fuzzification

The purpose of fuzzification is to map the inputs from a set of devices (for example sensors or features of those sensors such as amplitude or spectrum) to values from 0 to 1 using a set of input membership functions. In the schematic diagram shown in Figure 4.1, there are two inputs, x_0 and y_0 shown at the lower left corner. These inputs are mapped into fuzzy numbers by drawing a line up from the inputs to the input membership functions above and marking the intersection point.

These input membership functions, can represent fuzzy concepts such as "large" or "small", "old" or "young", "hot" or "cold", etc. The membership functions could then represent "large" amounts of tension coming from a muscle or "small" amounts of tension. When choosing the input membership functions, the definition of what we mean by "large" and "small" may be different for each input.

4.3.5. Defuzzification of Output Distribution

In many situations, for a system whose output is fuzzy, it is easier to take a crisp decision if the output is represented as a single scalar quantity. This conversion of a fuzzy set to single crisp value is called defuzzification and is the reverse process of fuzzification.

There are two common methods for defuzzification generally followed:

Centroid Method: Also known as the centre of gravity or the centre of area method, it obtains the centre of area (x^*) occupied by the fuzzy set. It is given by the expression;

$$x^* = \frac{\int \mu(x)\, x\, dx}{\int \mu(x)\, dx} \quad \text{(For a continuous membership function)} \qquad (4.1)$$

$$x^* = \frac{\sum_{i=1}^{n} x_i \, \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)} \text{ (For a discrete membership function)} \tag{4.2}$$

Here, 'n' represents the numbers of element in the sample, x_i's are the elements, and $\mu(x_i)$ is its membership function.

Mean of maxima (MOM) defuzzification method: One simple way of defuzzifying the output is to take the crisp value with the highest degree of membership. In case with more than one element having the maximum value, the mean value of the maxima is taken. The equation of the defuzzified value x^* is given by;

$$x^* = \frac{\sum_{x_i \in M} x_i}{|M|} \tag{4.3}$$

Where M= $\{x_i \mid \mu(x_i) \text{ is equal to the height of fuzzyset}\}$

$|M|$ is the cardinality of the set M. In the continuous case, M could be defined as

M= $\{x_i \in [-c, c] \mid \mu(x_i) \text{ is equal to the height of the fuzzyset}\}$

In such a case, the mean of maxima is the arithmetic average of mean values of all intervals contained in M including zero length intervals.

The height of a fuzzy set A, i.e. h(A) is the largest membership grade obtained by any element in that set.

4.4. Fuzzy Mechanism used for localization and identification of crack

The fuzzy controller has been developed (as shown in Figure: 4.3) where there are 3 inputs and 2 outputs parameter. The natural linguistic representations for the input are as follows

Relative first natural frequency = "FNF"

Relative second natural frequency = "SNF"

Relative third natural frequency = "TNF"

The natural linguistic term used for the outputs are

Relative crack depth = "RCD"

Relative crack length= “RCL”

Based on the above fuzzy subset the fuzzy rules are defined in a general form as follows:

If (FNF is FNFi and SNF is SNFj and TNF is TNFk) then (CD is CDijk and CL is CLijk)

Where i= 1to 9, j=1 to 9, k=1 to 9 (4.4)

Because of “FNF”, “SNF”, “TNF” have 9 membership functions each.

From the above expression (4.4), two set of rules can be written

If (FNF is FNFi and SNF is SNFj and TNF is TNFk) then CD is CDijk (4.5a)

If (FNF is FNFi and SNF is SNFj and TNF is TNFk) then CL is CLijk (4.5b)

According to the usual Fuzzy logic control method (Das and Parhi [1]), a factor Wijk is defined for the rules as follows:

Wijk=μfnfi (freqi) Λ μsnfj (freqj) Λ μtnfi (freqk)

Where freqi, freqj and freqk are the first, second and third natural frequency of the cantilever beam with crack respectively ; by Appling composition rule of interference (Das and Parhi [1]) the membership values of the relative crack location and relative crack depth (location)CL.

μrclijk (location) = Wijk Λ μrclijk (location) length CL

As;

μrclijk (depth) = Wijk Λ μrclijk (depth) depth CD

The overall conclusion by combining the output of all the fuzzy can be written as follows:

μrclijk (location) = μrcl111 (location) V.….V μrclijk (location)

V.V μrcl9 9 9 (location) (4.6a)

μrclijk (location) = μrcl111 (depth) V.…..V μrclijk (depth)

V….V μrcl9 9 9 (depth) (4.6b)

The crisp values of relative crack location and relative crack depth are computed using the center of gravity method (Das and Parhi [1]) as:

$$\text{Relative crack location=rcl=}\ \frac{\int \text{location}.\mu_{rcl}(\text{location}).d(\text{location})}{\int \mu_{rcl}(\text{location}).d(\text{location})} \tag{4.7a}$$

$$\text{Relative crack depth=rcd=}\ \frac{\int \text{depth}.\mu_{rcd}(\text{depth}).d(\text{depth})}{\int \mu_{rcd}(\text{depth}).d(\text{depth})} \tag{4.8b}$$

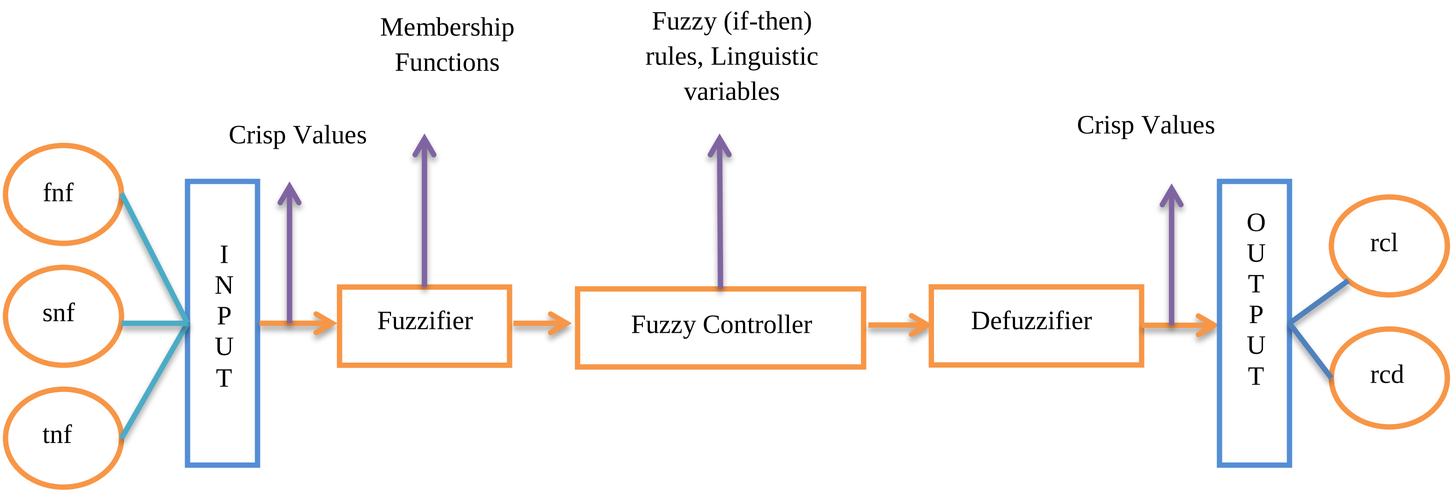


Figure: 4.3 Schematic diagram of Fuzzy Inference System

4.5. Function of Fuzzy Controller for Localization and Identification of Crack

The inputs to the fuzzy controller are relative first natural frequency; relative second natural frequency; relative third natural frequency. The outputs from the fuzzy controller are relative crack depth and relative crack location. Several hundred fuzzy rules are outlined to train the fuzzy controller. Twenty four numbers of the fuzzy rules out of several hundred fuzzy rules are being listed in Table: 4.2. The output data has been generated from the input data and the rule base.

$$\text{Relative Natural Frequency} = \frac{\text{Natural frequency of uncracked beam}}{\text{Natural frequency of cracked beam}}$$

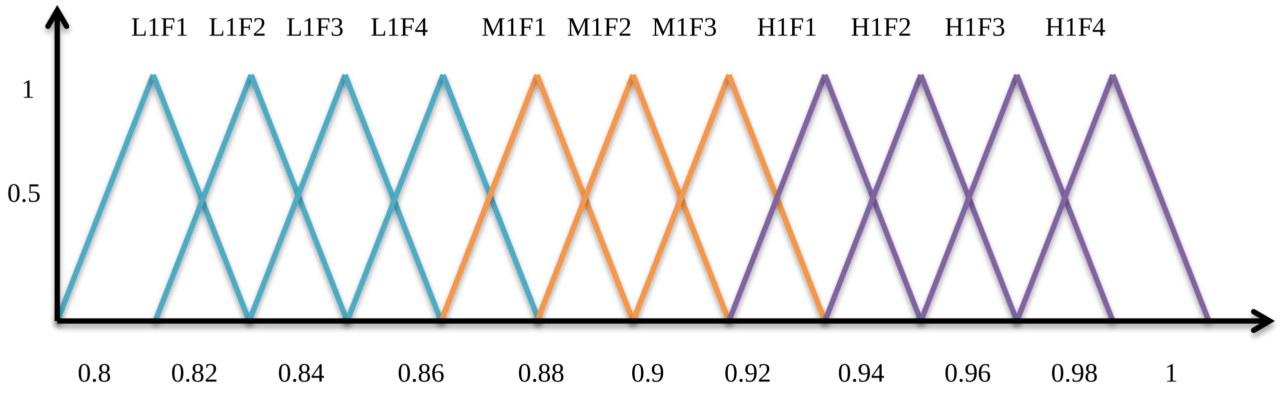


Figure: 4.4(a) Triangular Membership functions for relative natural frequency for 1st mode of vibration

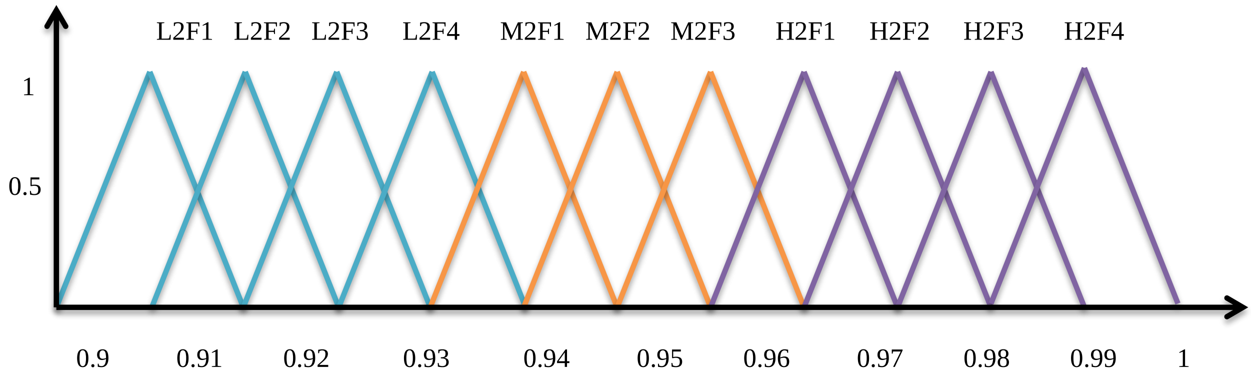


Figure: 4.4(b) Triangular Membership functions for relative natural frequency for 2nd mode of vibration

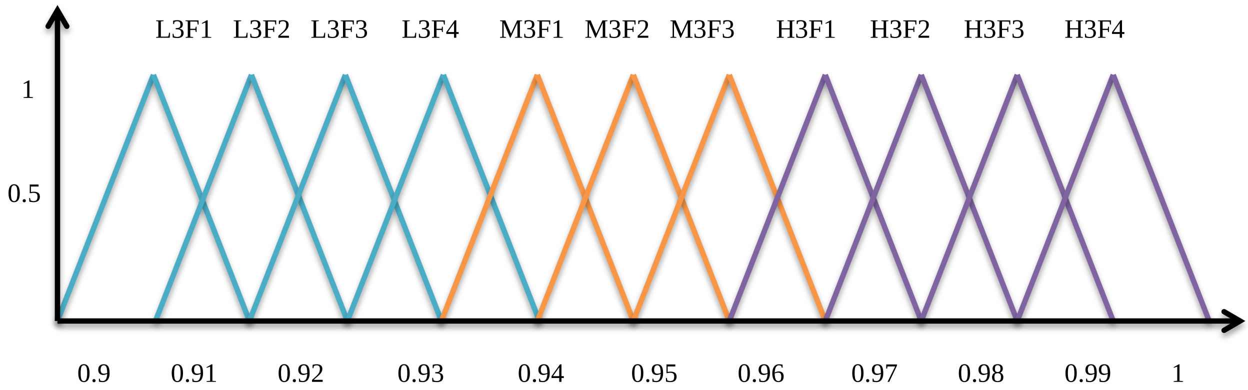


Figure: 4.4(c) Triangular Membership functions for relative natural frequency for 3rd mode of vibration

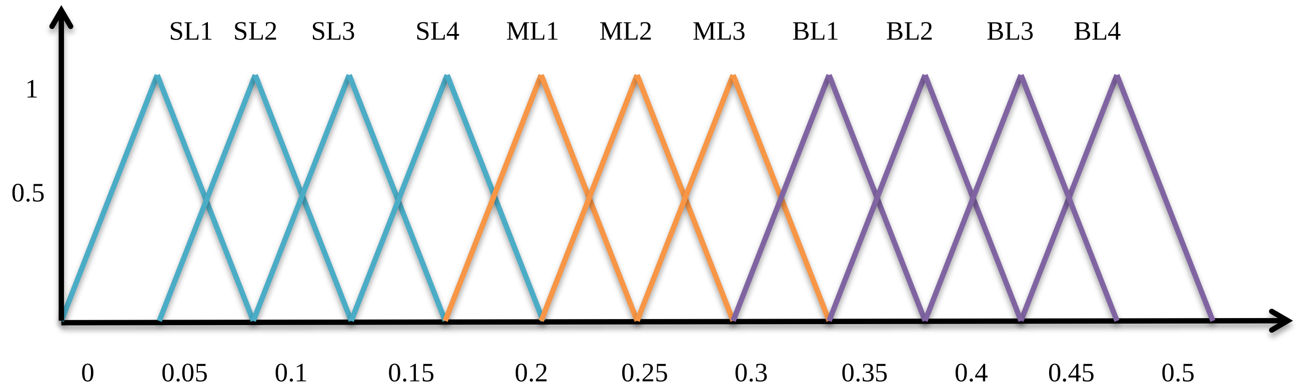


Figure: 4.4(d) Triangular Membership functions for relative crack location

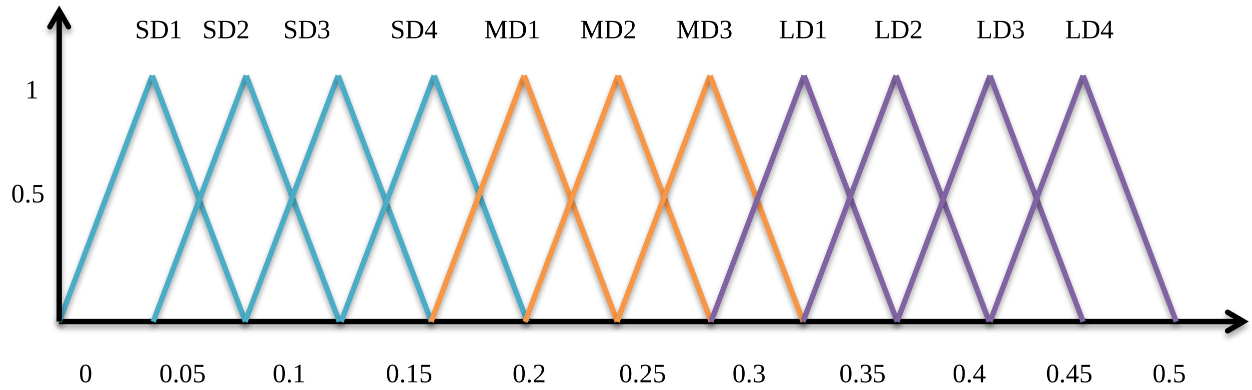


Figure: 4.4(e) Triangular Membership functions for relative crack depth

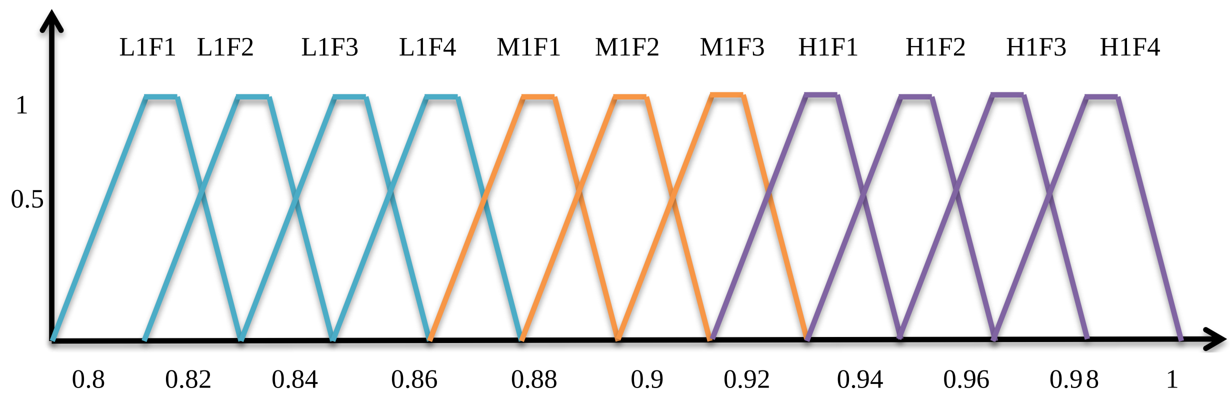


Figure: 4.5(a) Trapezoidal Membership functions for relative natural frequency for 1st mode of vibration

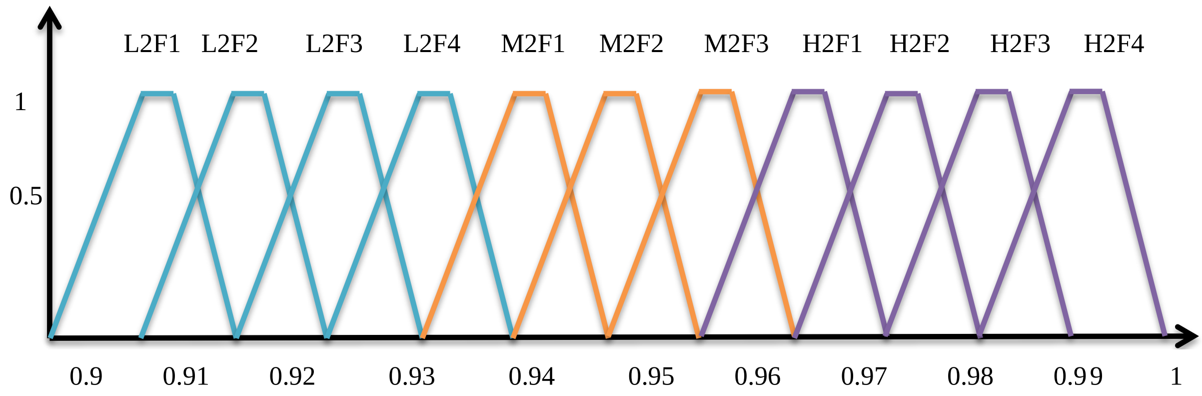


Figure: 4.5(b) Trapezoidal Membership functions for relative natural frequency for 2nd mode of vibration

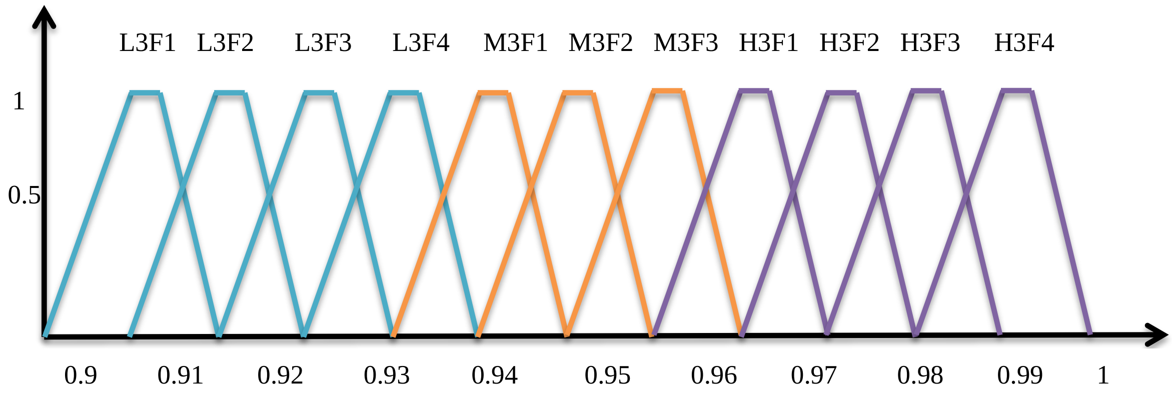


Figure: 4.5(c) Trapezoidal Membership functions for relative natural frequency for 3rd mode of vibration

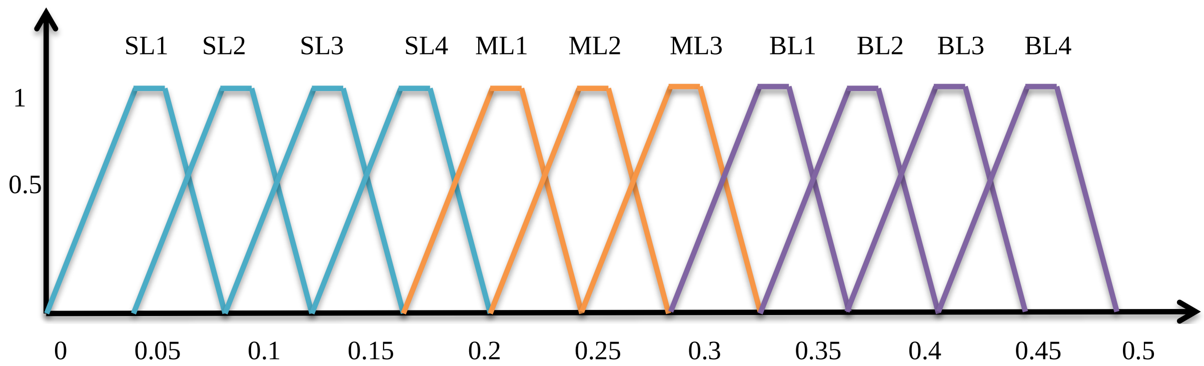


Figure: 4.5(d) Trapezoidal Membership functions for relative crack location

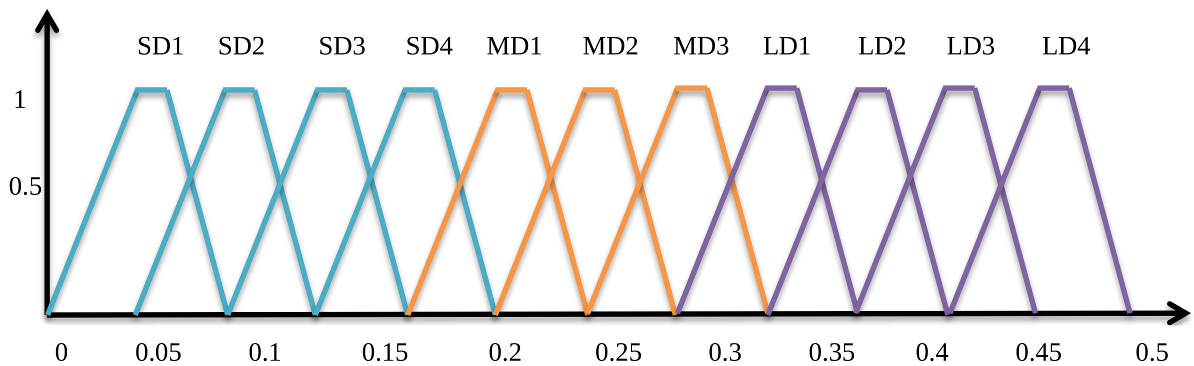


Figure: 4.5(e) Trapezoidal Membership functions for relative crack depth

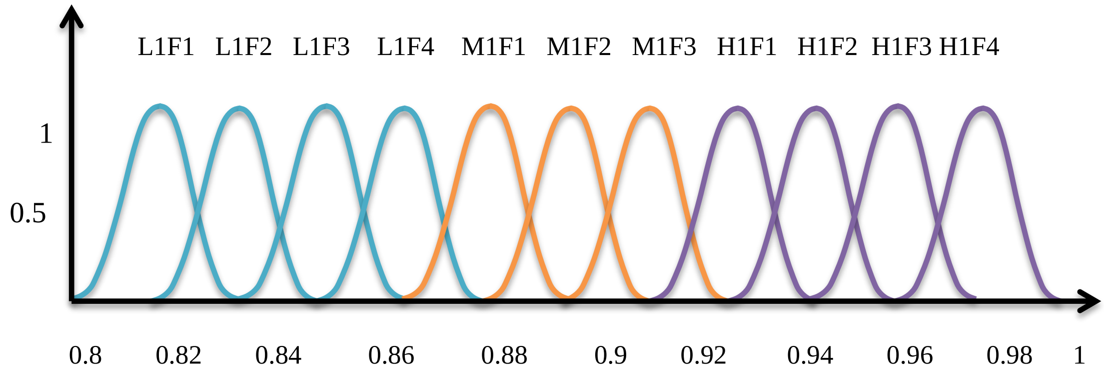


Figure: 4.6(a) Gaussian Membership functions for relative natural frequency for 1st mode of vibration

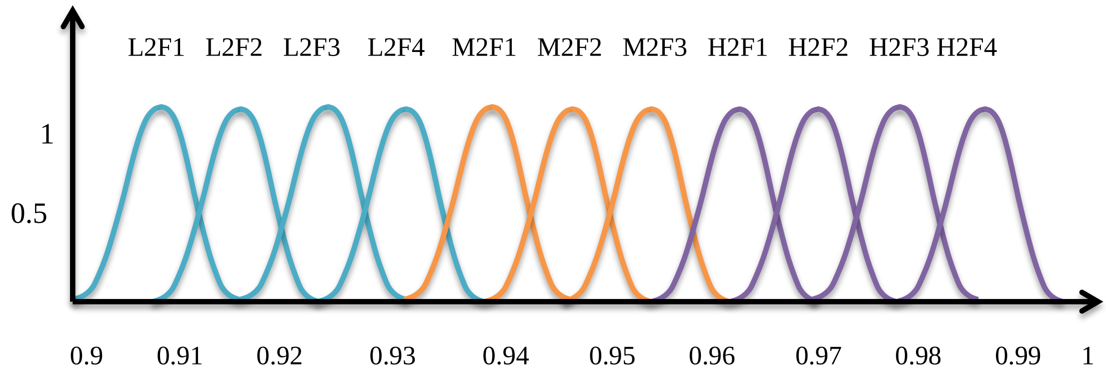


Figure: 4.6(b) Gaussian Membership functions for relative natural frequency for 2nd mode of vibration

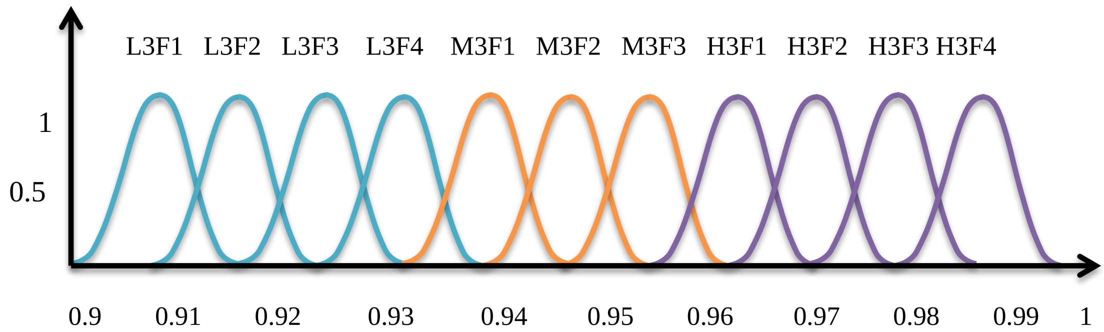


Figure: 4.6(c) Gaussian Membership functions for relative natural frequency for 3rd mode of vibration

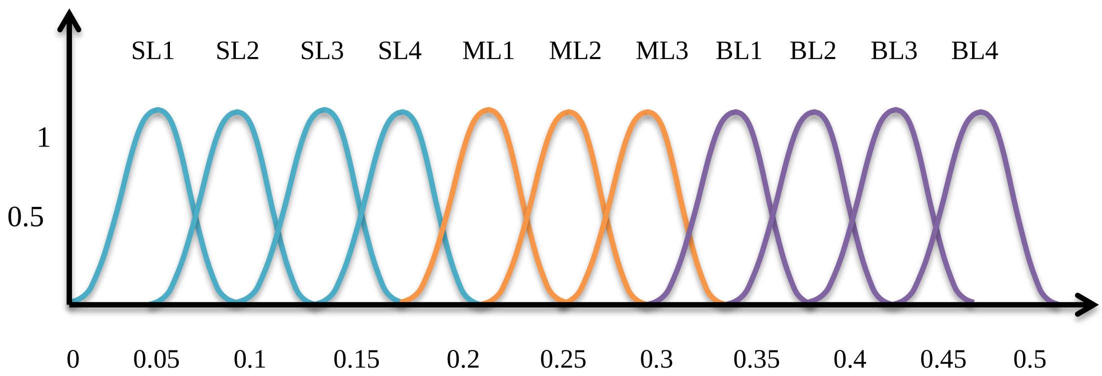


Figure: 4.6(d) Gaussian Membership functions for relative crack location

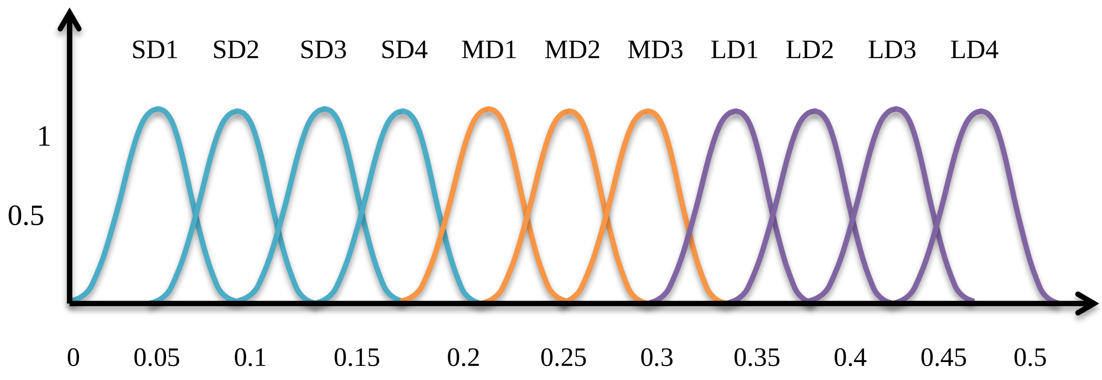


Figure: 4.6(e) Gaussian Membership functions for relative crack depth

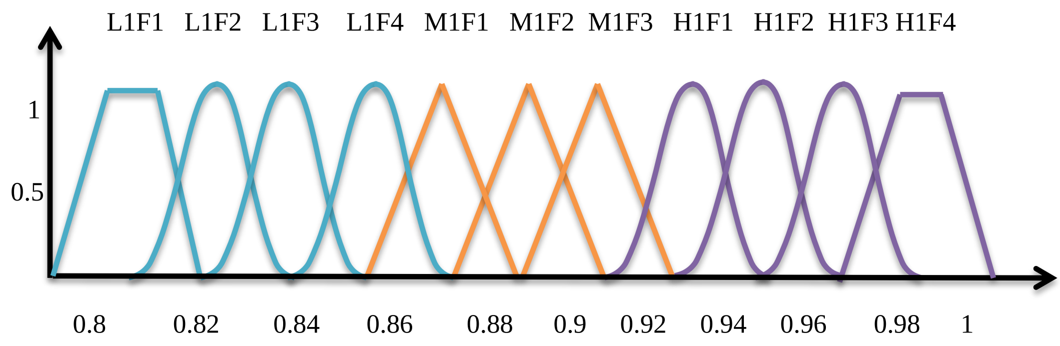


Figure: 4.7(a) Hybrid Membership functions for relative natural frequency for 1st mode of vibration

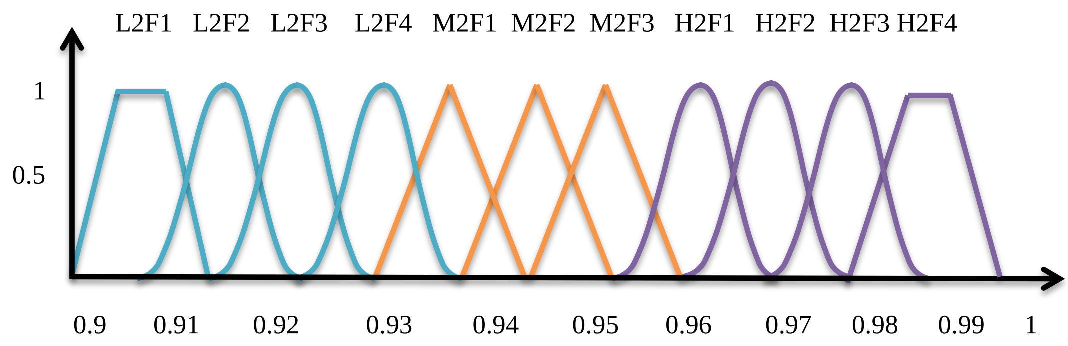


Figure: 4.7(b) Hybrid Membership functions for relative natural frequency for 2nd mode of vibration

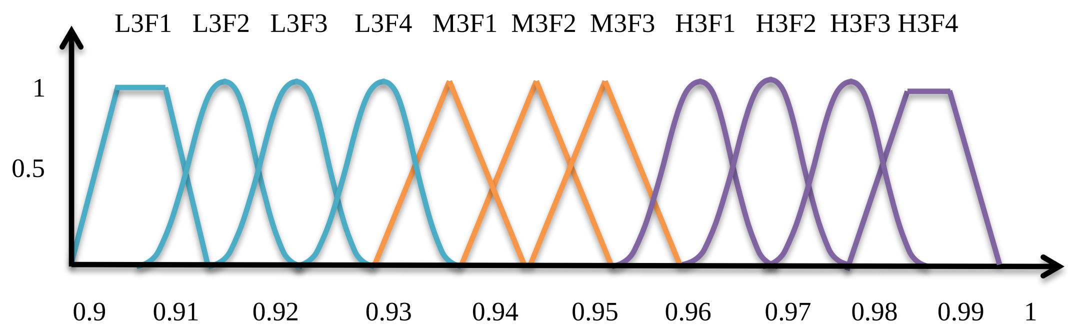


Figure: 4.7(c) Hybrid Membership functions for relative natural frequency for 3rd mode of vibration

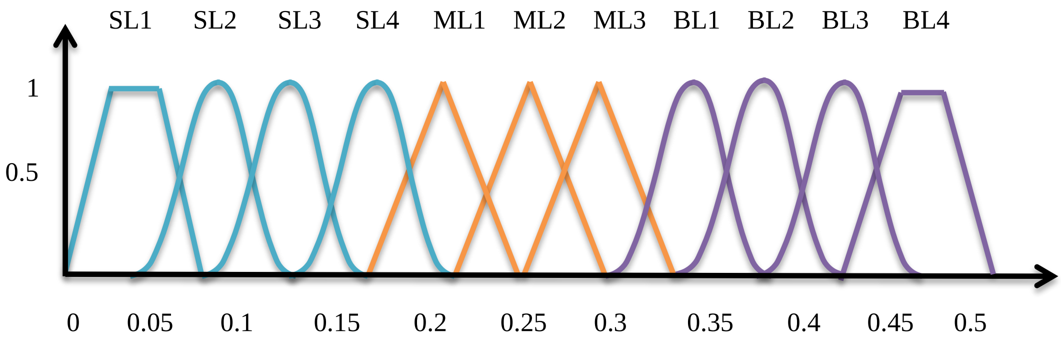


Figure: 4.7(d) Hybrid Membership functions for relative crack location

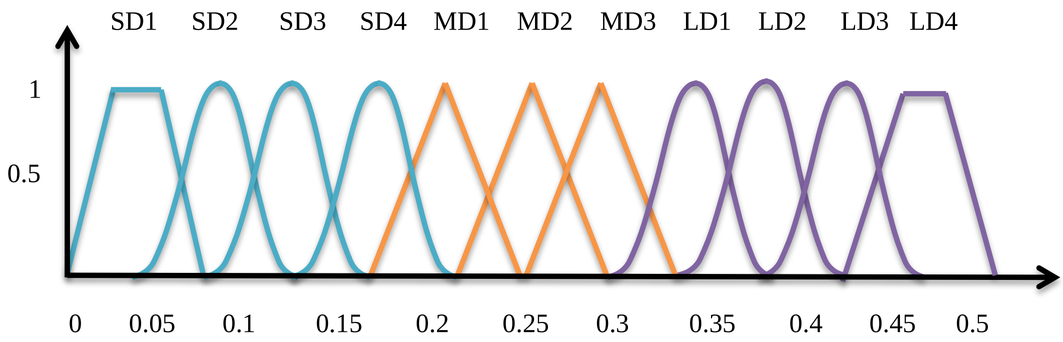


Figure: 4.7(e) Hybrid Membership functions for relative crack depth

4.5.1. Discussion

In this current research the fuzzy controller has been designed using four types of membership functions, i.e. triangular (Figure: 4.4), trapezoidal (Figure: 4.5), Gaussian (Figure: 4.6) and hybrid membership function (Figure: 4.7) which combines trapezoidal, Gaussian as well as triangular membership functions. By taking the consideration of triangular membership functions the Figure: 4.4(a) shows the various linguistic terms used for the Relative 1st mode natural frequency. It has total 11 number of membership functions. Similarly Figure: 4.4(b) and 4.4(c) show the membership functions and the respective linguistic terms used for 2nd and 3rd mode relative natural frequencies. And both are having 11 membership functions each. Figure: 4.4(d) and 4.4(e) represents the membership functions and respective linguistic terms used for output of fuzzy controller, i.e. the linguistic terms used for relative crack location and relative crack depth. The similar linguistic terms are also used for other membership functions are as shown in the figures (Figure: 4.5 to 4.7). The working principle for the fuzzy inference system has been depicted in Figure: 4.3. The linguistic terms used in the fuzzy membership function has been specified in Table: 4.1. The fuzzy rules being used for the fuzzy inference system are specified in the Table: 4.2. Out of several hundreds of fuzzy rules only twenty four fuzzy rules has been indicated in the table. Figure: 4.8 to Figure: 4.11 shows the operation of fuzzy inference system to exhibits the fuzzy results after defuzzification when rule 3 and 12 of the Table: 4.2 are activated for triangular, trapezoidal, Gaussian and hybrid membership functions respectively. The comparison of the results obtained from theoretical and the fuzzy controller with triangular membership function, fuzzy controller with trapezoidal membership function, fuzzy controller with Gaussian membership function and fuzzy controller with hybrid membership functions are presented in Table: 4.3 at the end of this Chapter and also a comparison of result shown between different fuzzy controllers and the kohonen network technique in Chapter 7.

Table: 4.1 Linguistic Terms used for Fuzzy Membership Functions

Name of the Membership functions	Linguistic terms	Description and range of the linguistic terms
L1F1,L1F2,L1F3,L1F4	fnf_{1to4}	Low ranges of relative natural frequency for first mode of vibration in ascending order respectively.
M1F1,M1F2,M1F3	fnf_{5to7}	Medium ranges of relative natural frequency for first mode of vibration in ascending order respectively.
H1F1,H1F2,H1F3,H1F4	fnf_{8to11}	Higher ranges of relative natural frequency for first mode of vibration in ascending order respectively
L2F1,L2F2,L2F3,L2F4	snf_{1to4}	Low ranges of relative natural frequency for second mode of vibration in ascending order respectively.
M2F1,M2F2,M2F3	snf_{5to7}	Medium ranges of relative natural frequency for second mode of vibration in ascending order respectively.
H2F1,H2F2,H2F3,H2F4	snf_{8to11}	Higher ranges of relative natural frequency for first mode of vibration in ascending order respectively
L3F1,L3F2,L3F3,L3F4	tnf_{1to4}	Low ranges of relative natural frequency for second mode of vibration in ascending order respectively
M3F1,M3F2,M3F3	tnf_{5to7}	Medium ranges of relative natural frequency for second mode of vibration in ascending order respectively
H3F1,H3F2,H3F3,H3F4	tnf_{8to11}	Higher ranges of relative natural frequency for first mode of vibration in ascending order respectively
SD1,SD2,SD3,SD4	rcd_{1to4}	Small ranges of relative crack depth in ascending order respectively.

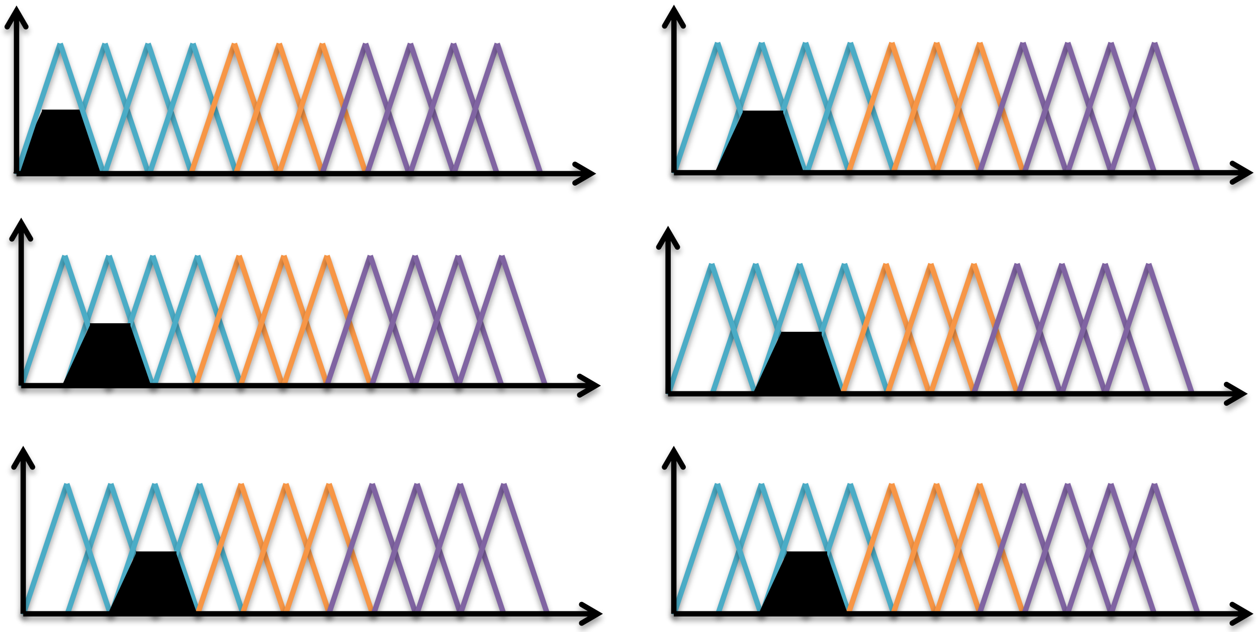
MD1,MD2,MD3	rcd_{5to7}	Medium ranges of relative crack depth in ascending order respectively
LD1,LD2,LD3,LD4	rcd_{8to11}	Larger ranges of relative crack depth in ascending order respectively.
SL1,SL2,SL3,SL4	rcl_{1to4}	Small ranges of relative crack location in ascending order respectively.
ML1,ML2,ML3	rcl_{5to7}	Medium ranges of relative crack location in ascending order respectively.
BL1,BL2,BL3,BL4	rcl_{8to11}	Bigger ranges of relative crack location in ascending order.

Table: 4.2 Fuzzy Rules for Fuzzy Inference System

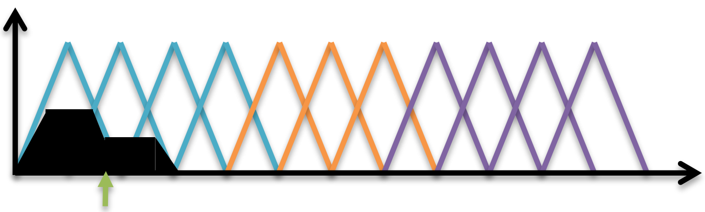
Sl. No	Some Examples of Fuzzy rule used in the Fuzzy Controller
1	If fnf is L1F1, snf is L2F1, tnf is L3F1 then rcd is SD1 and rcl is SL1
2	If fnf is L1F1, snf is L2F2, tnf is L3F2 then rcd is SD2 and rcl is SL2
3	If fnf is L1F1, snf is L2F2, tnf is L3F3 then rcd is SD1 and rcl is SL2
4	If fnf is M1F1, snf is M2F1, tnf is M3F1 then rcd is MD1 and rcl is ML1
5	If fnf is M1F1, snf is M2F2, tnf is M3F2 then rcd is MD2 and rcl is ML2
6	If fnf is M1F1, snf is M2F2, tnf is M3F3 then rcd is MD1 and rcl is ML2
7	If fnf is M1F2, snf is M2F1, tnf is M3F1 then rcd is MD2 and rcl is ML1
8	If fnf is M1F2, snf is M2F2, tnf is M3F2 then rcd is MD2 and rcl is ML3
9	If fnf is M1F3, snf is M2F1, tnf is M3F2 then rcd is MD3 and rcl is ML1
10	If fnf is M1F2, snf is M2F3, tnf is M3F2 then rcd is MD1 and rcl is ML3
11	If fnf is L1F2, snf is L2F1, tnf is L3F1 then rcd is SD2 and rcl is SL1
12	If fnf is L1F2, snf is L2F3, tnf is L3F3 then rcd is SD2 and rcl is SL3
13	If fnf is L1F3, snf is L2F1, tnf is L3F2 then rcd is SD3 and rcl is SL1
14	If fnf is L1F2, snf is L2F3, tnf is L3F2 then rcd is SD1 and rcl is SL3
15	If fnf is L1F3, snf is L2F3, tnf is L3F3 then rcd is SD3 and rcl is SL3
16	If fnf is M1F3, snf is M2F3, tnf is M3F3 then rcd is MD3 and rcl is ML3
17	If fnf is H1F1, snf is H2F1, tnf is H3F1 then rcd is LD1 and rcl is BL1
18	If fnf is H1F1, snf is H2F2, tnf is H3F2 then rcd is LD2 and rcl is BL2
19	If fnf is H1F1, snf is H2F3, tnf is H3F3 then rcd is LD1 and rcl is BL2
20	If fnf is H1F2, snf is H2F1, tnf is H3F1 then rcd is LD2 and rcl is BL1
21	If fnf is H1F2, snf is H2F2, tnf is H3F2 then rcd is LD2 and rcl is BL3
22	If fnf is H1F3, snf is H2F1, tnf is H3F2 then rcd is LD3 and rcl is BL1
23	If fnf is H1F2, snf is H2F3, tnf is H3F2 then rcd is LD1 and rcl is BL3
24	If fnf is H1F3, snf is H2F3, tnf is H3F3 then rcd is LD3 and rcl is BL3

Inputs for triangular membership function

Rule No. 3 of Table: 4.2 is activated **Rule No.12 of Table: 4.2 is activated**

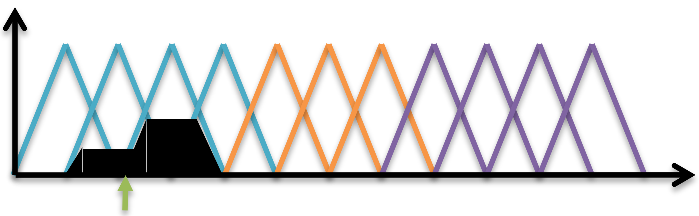


Outputs obtain from triangular membership function



0.169

Relative Crack Depth



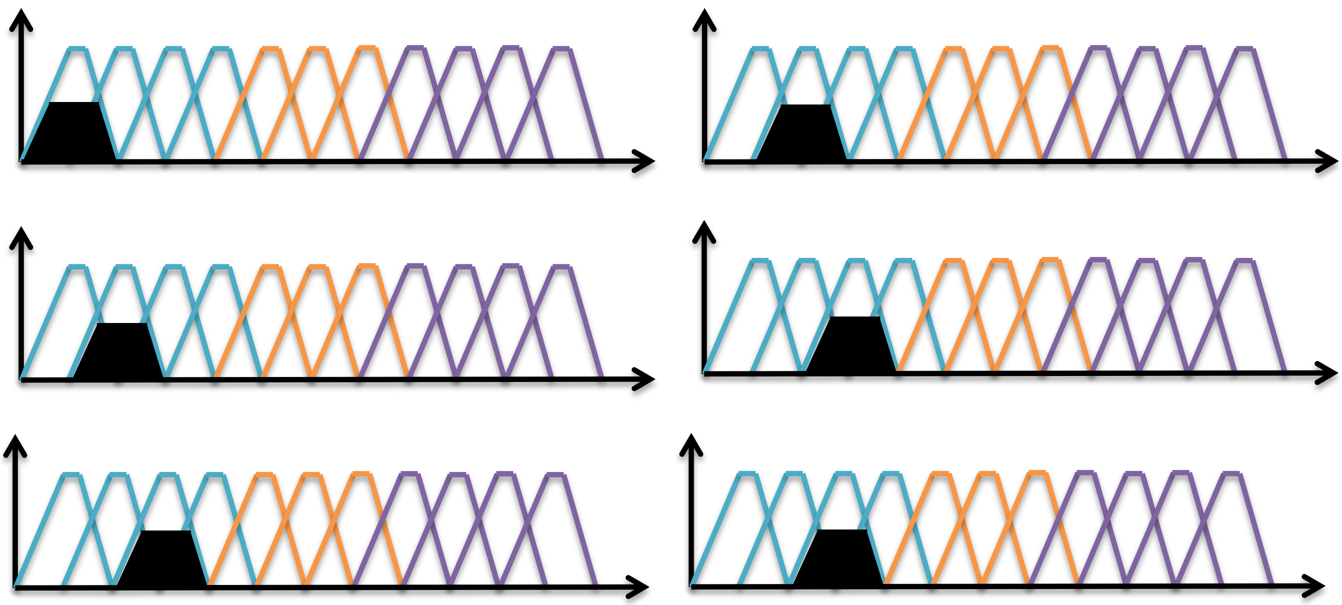
0.255

Relative Crack Location

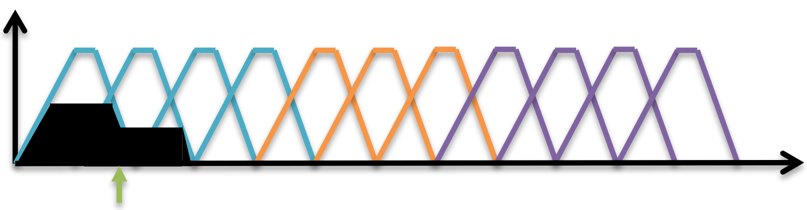
Figure: 4.8 Resultant values of relative crack depth and relative crack location of triangular membership function when Rules 3 and 12 of Table: 4.2 are activated

Inputs for trapezoidal membership function

Rule No. 3 of Table: 4.2 is activated **Rule No.12 of Table: 4.2 is activated**

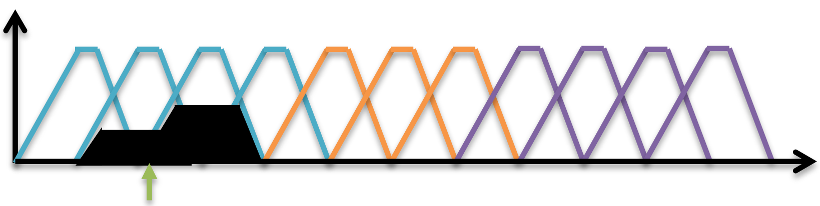


Outputs obtain from trapezoidal membership function



0.170

Relative Crack Depth



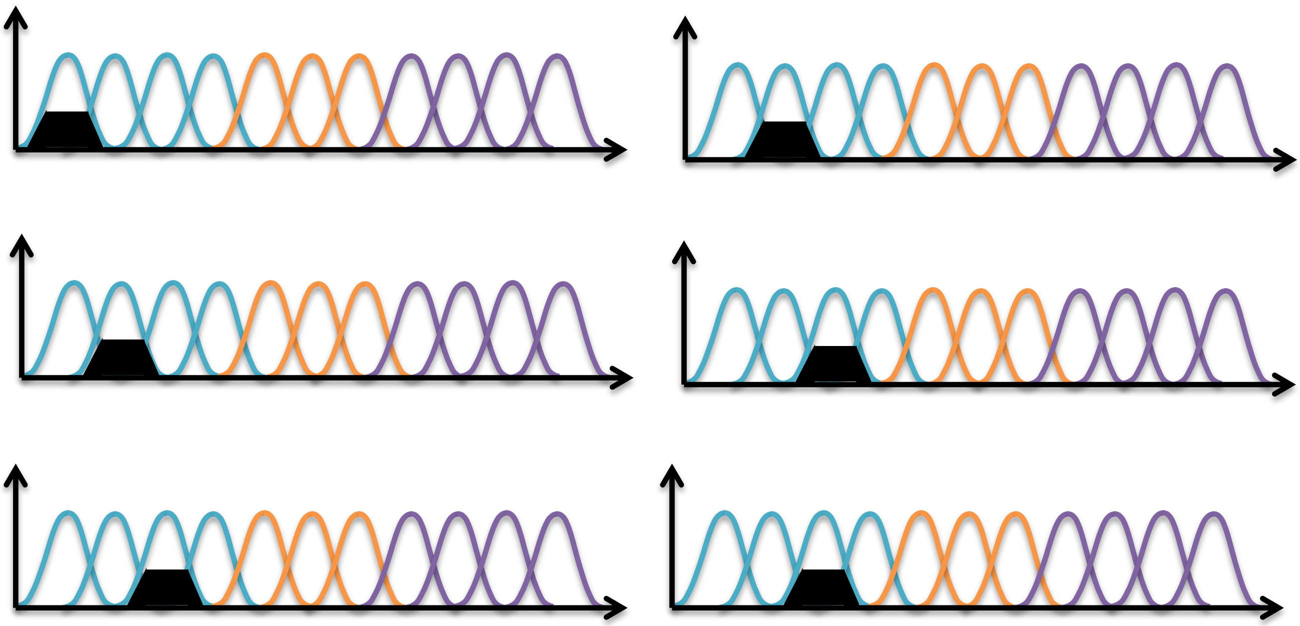
0.260

Relative Crack Location

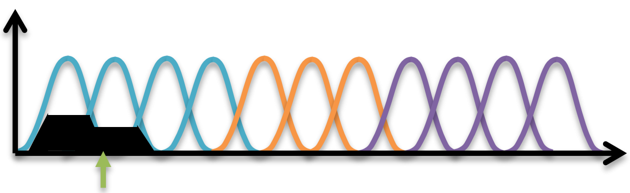
Figure: 4.9 Resultant values of relative crack depth and relative crack location of trapezoidal membership function when Rules 3 and 12 of Table: 4.2 are activated

Inputs for Gaussian membership function

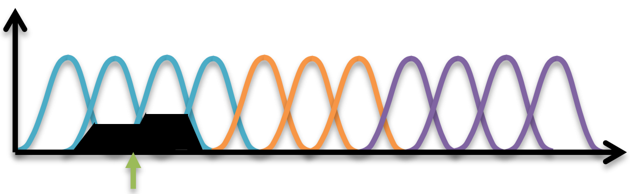
Rule No. 3 of Table: 4.2 is activated **Rule No.12 of Table: 4.2 is activated**



Outputs obtain from Gaussian membership function



Relative Crack Depth

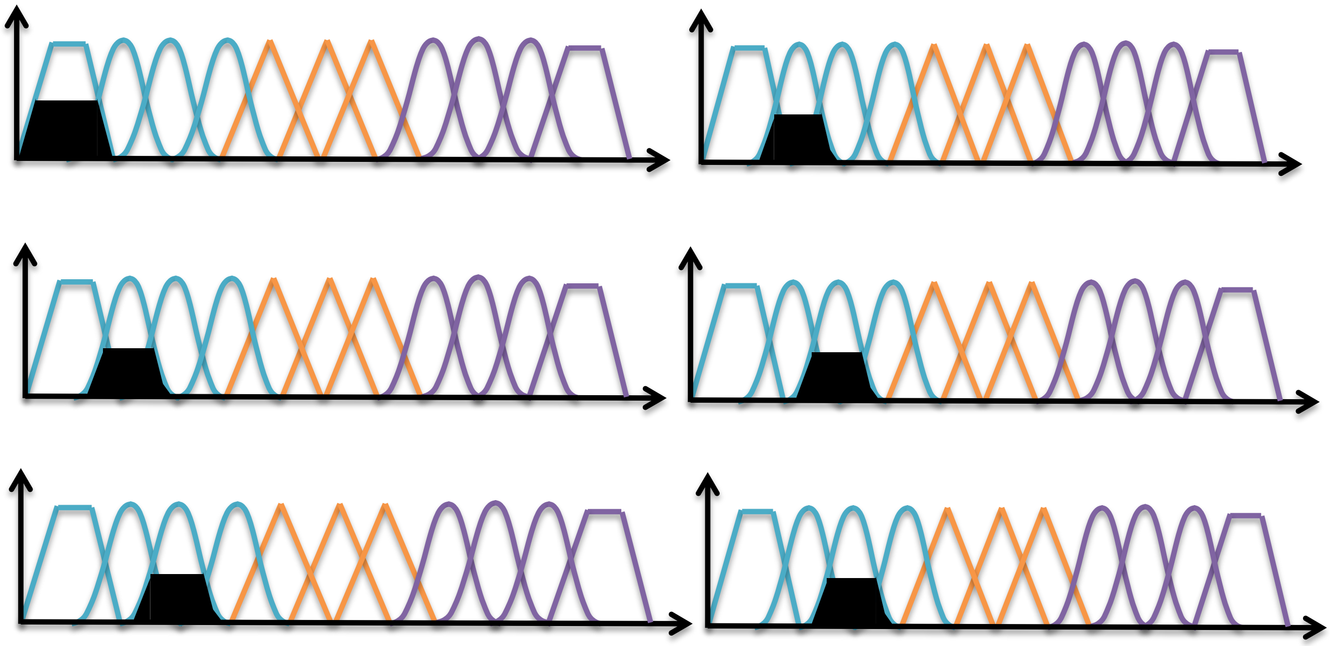


Relative Crack Location

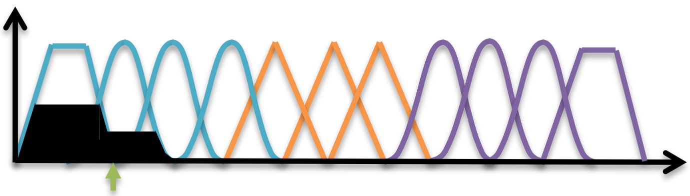
Figure: 4.10 Resultant values of relative crack depth and relative crack location of Gaussian membership function when Rules 3 and 12 of Table: 4.2 are activated

Inputs for Hybrid membership function

Rule No. 3 of Table: 4.2 is activated **Rule No.12 of Table: 4.2 is activated**

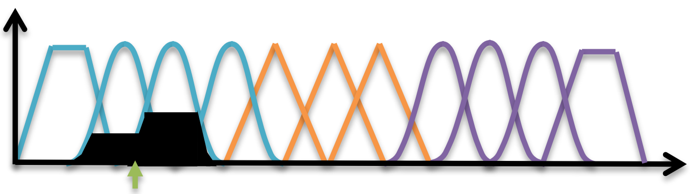


Outputs obtain from Hybrid membership function



0.161

Relative Crack Depth



0.262

Relative Crack Location

Figure: 4.11 Resultant values of relative crack depth and relative crack location of hybrid membership function when Rules 3 and 12 of Table: 4.2 are activated

4.5.2. Comparison of Results

Table: 4.3 Comparison of Results between Theoretical Analysis and different Fuzzy Controller Analysis

Relative First natural frequency fnf	Relative Second natural frequency snf	Relative Third natural frequency tnf	Theoretical		Triangular Fuzzy Controller		Trapezoidal Fuzzy Controller		Gaussian Fuzzy Controller		Hybrid Fuzzy Controller	
			Relative crack depth rcd	Relative crack location rcl	rcd	rcl	rcd	rcl	rcd	rcl	rcd	rcl
0.8142	0.9537	0.9266	0.3167	0.125	0.314	0.124	0.315	0.126	0.316	0.125	0.316	0.128
0.8635	0.9737	0.9335	0.3	0.1875	0.296	0.189	0.297	0.190	0.298	0.190	0.305	0.186
0.9013	0.9813	0.9470	0.2834	0.25	0.280	0.255	0.285	0.260	0.281	0.245	0.287	0.262
0.9315	0.9867	0.9523	0.2667	0.3125	0.270	0.320	0.272	0.323	0.268	0.313	0.261	0.312
0.9544	0.9888	0.9664	0.25	0.375	0.252	0.379	0.252	0.382	0.245	0.372	0.245	0.379
0.9692	0.9905	0.9757	0.2334	0.4375	0.240	0.442	0.239	0.445	0.233	0.440	0.224	0.425
0.9839	0.9917	0.9845	0.2167	0.5	0.224	0.505	0.227	0.495	0.214	0.512	0.215	0.498
0.9908	0.9946	0.9855	0.2	0.5625	0.213	0.571	0.212	0.565	0.21	0.561	0.23	0.567
0.9964	0.9967	0.9993	0.1834	0.625	0.185	0.635	0.179	0.637	0.182	0.629	0.182	0.632
0.9986	0.9980	0.9994	0.1667	0.6875	0.169	0.69	0.170	0.72	0.165	0.687	0.161	0.681

4.5.3. Summary

A fuzzy controller has been designed, which uses three natural frequencies as inputs where as the crack depth and crack location as output. It has been observed that the natural frequency of the beam is changing with Crack depth and crack location. The predicted results from fuzzy controllers for crack location and crack depth are compared with the theoretical results. It is observed from the Table: 4.3 that the results obtained from Gaussian membership function fuzzy controller predict more accurate result in comparison to other three controllers.

4.6. Why Fuzzy Logic is Used

✓ Provides an easy to use interface for applying modern fuzzy logic techniques.

✓ Does not require mathematical formulation.

✓ Powerful tool for dealing with imprecision, uncertainty.

✓ Precision is traded for tractability, robustness and low cost solution.

- ✓ Provides the ability to use fuzzy logic when appropriate with other control techniques.
- ✓ It may be used for real world model like behavior of a human being.
- ✓ Supplies a fuzzy inference engine that can execute the fuzzy system as a stand-alone application.

CHAPTER 5

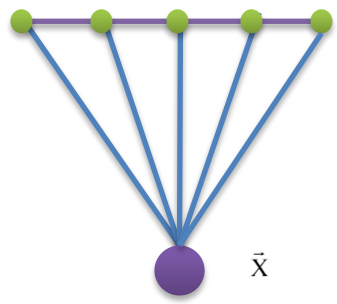
ANALYSIS OF KOHONEN NETWORK FOR IDENTIFICATION OF CRACK

CHAPTER 5 Analysis of Kohonen Network for Identification of Crack

5.1. Introduction

The Self-Organizing Map (SOM), commonly also known as Kohonen network (Kohonen 1982, Kohonen 2001) is a computational method for the visualization and analysis of high-dimensional data, especially experimentally acquired information [53]. The self-organizing map (SOM) network was originally designed for solving problems that involve tasks such as clustering, visualization, and abstraction. While Kohonen's SOM networks have been successfully applied as a classification tool to various problem domains, their potential as a robust substitute for clustering and visualization analysis remains relatively un researched. The self-organizing map (SOM) network is a special type of neural network that can learn from complex, multi-dimensional data and transform them into visually decipherable clusters. The Kohonen network (Kohonen, 1982, 1984) can be seen as an extension to the competitive learning network, although this is chronologically incorrect. Also, the Kohonen network has a different set of applications. In the Kohonen network, the output units are ordered in some fashion, often in a two dimensional grid or array, although this is application-dependent. The ordering, which is chosen by the user1, determines which output neurons are neighbors. The main function of SOM networks is to map the input data from an n-dimensional space to a lower dimensional (usually one or two-dimensional) plot while maintaining the original topological relations. The physical location of points on the map shows the relative similarity between the points in the multi-dimensional space. Competitive learning (Kohonen, 1982) is a special case of Self organizing Map.

In Self-Organizing Map, it Transform as input signal pattern of arbitrary dimension into one or two dimensional discrete map, Perform this transformation adaptively in a topological ordered fashion. Winner takes all neuron. Two possible architectures are existing in Kohonen Network, which are shown in Figure: 5.1.



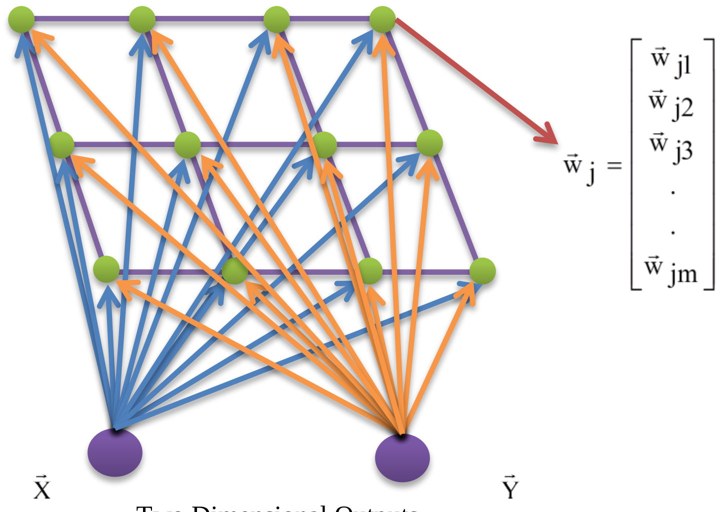


Figure: 5.1 Possible Architectures in Kohonen Network

5.2. Essential Processes of Kohonen Network/ the SOM Training Algorithm

The SOM network typically has two layers of nodes, the input layer and the Kohonen layer. The input layer is fully connected to a two-dimensional Kohonen layer. During the training process, input data are fed to the network through the processing elements (nodes) in the input layer. An input pattern x_m (m=1, 2, 3…, m) is denoted by a vector of order m as: x_m =(x_1, x_2… x_m), where x_m is the mth input signal in the pattern and m is the number of input signals in each pattern. An input pattern is simultaneously incident on the nodes of a two-dimensional Kohonen layer. Associated with the N nodes in the m × l (N =m × l) Kohonen layer, is a weight vector, also of order l; denoted by: w_j = (w_{j1}, w_{j2}… w_{jl}), where w_{jl} is the weight value associated with node j corresponding to the lth signal of an input vector. As the training process proceeds, the nodes adjust their weight values according to the topological relations in the input data. The node with the minimum distance is the winner and adjusts its weights to be closer to the value of the input pattern. In this study, Euclidean distance is the most common way of measuring distance between vectors, is used. The procedure with details being as follows.

5.2.1. Initialization

Each nodes weight is initialized. A vector is chosen at random from the set of training data and presented to the lattice. When the input vector is presented to the map, its distance to the weight vector of each node is computed. The map returns the closest node which is called the *Best Matching Unit* (BMU).

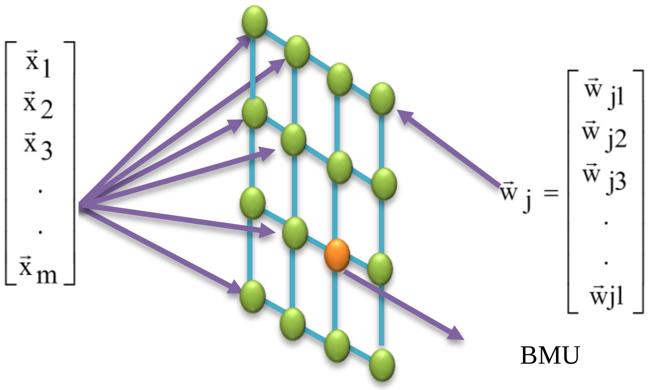


Figure: 5.2 Process of Initialization in Kohonen Network

5.2.2. Competitive Process

It is also called long range inhibition*. For each input pattern, the neurons in the output layer will determine the value of a function. That function will be calling as the discriminant function. Each neuron computes a discriminant function. The neuron with largest discriminant function is the winner.

"A continuous input space of activation pattern is mapped onto a discrete output space of neurons by a process of competition among the neurons in the network".

$$\text{Winner neuron} = \arg_j \max(\vec{w}_j^{\,T}\vec{x}) = \arg_j \min(\|\vec{x} - \vec{w}_j\|) \tag{5.1}$$

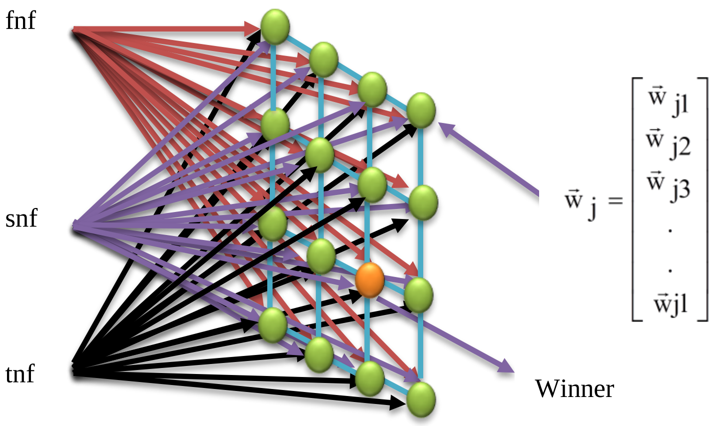


Figure: 5.3 Process of Competition in Kohonen Network

5.2.3. Co-operative Process

It is also called short range excitation*. The winning neuron locates the Centre of a topological neighborhood of co-operating neurons. A neuron that is firing tends to excite the neurons in its immediate neighborhood more than those farther away from it. Excitation is a co-operation. It strengthens the neuron which are closer to winner, where as the process of competition the neurons which are far apart, they are eliminated.

$$h_{ji} = \exp\left(\frac{-d^2{}_{j,i}}{2\sigma^2}\right) \tag{5.2}$$

*Neurons which are there at the output, they are act in a competitive manner, in the sense that they inhibit the responses of each other. The neurons which are close to the winning neuron, they tends to have an excitatory response; that means to say around the winning neuron an excitatory response is generally created where as an inhibitory response is created for the neurons which are there far distant apart. This short of networks will exhibit long range inhibition and short range excitation.

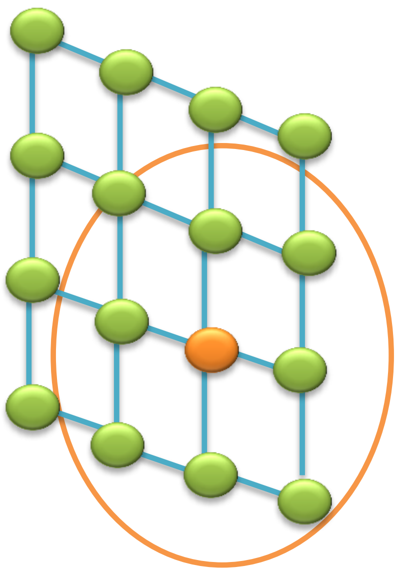


Figure: 5.4 Process of Co-operative in Kohonen Network

5.2.4. Synaptic Adaptation Process

It enables the excitation/excited neurons to increase their individual values of discriminant function in relation to the input pattern. The discriminant function values for the non-excited will be kept unchanged. Response of winning neuron is increased.

The output of the map is usually sent to another learning machine which will finish the process of pattern recognition.

5.3. Mechanism

The training of the Kohonen Network is done by a specific algorithm. The goal is to obtain a map where two points, which are nearby in the input space are also closed in the map. The algorithm of Kohonen network is processed through various mechanisms as explained below.

5.3.1. Competition Mechanism

$[\vec{x}] = [x_1, x_2, ..., x_m]^T$ Where, $\vec{x}$ is the input vector, m= Dimensional Input. (5.3)

$[\vec{w}_j] = [w_{j1}, w_{j2}, ..., w_j]^T$, j=1, 2, 3...l, l= Number of output neurons. (5.4)

$|\vec{w}_j|$= Weight Vector

Every output is connected to all input. There will be $m \times l$ number of arrays. We have to determine the best match between $\vec{x}$ and $\vec{w}_j$. Compute $\vec{w}_j^T \vec{x}$ for j=1, 2 …l.

Winning neuron= arg maximize $(\vec{w}_j^T \vec{x})$, we have to minimize the Euclidian distance $(\|\vec{x} - \vec{w}_j\|)$

$\Rightarrow$ Winner neuron= $\arg_j \max(\vec{w}_j^T \vec{x}) = \arg_i \min(\|\vec{x} - \vec{w}_j\|)$ (5.5)

5.3.2. Co-operative Mechanism

In addition to winning neuron all the neighborhood neuron should adjust their weights. Winning neuron: i

Topological neighborhood:

$h_{j,i}$: Topological neighborhood centered on i; encompassing neuron j.

$d_{j,i}$: Lateral distance between the winning neuron ‘i’ and excited neuron j.

Satisfying two properties:

Symmetric about $d_{j,i}\rightarrow 0$ and considering monotonically decaying function, we can get

$$h_{j,i}(\vec{x}) = \exp\left(\frac{-d^2{}_{j,i}}{2\sigma^2}\right), \tag{5.6}$$

σ =width of Gaussian function, σ is not constant with time/iteration. As the iteration processes, σ is going to be decrease. The topological neighborhood $h_{j,i}$ shrinks and narrow down with time.

$$\sigma(t) = \sigma_0 \exp\left(-\frac{t}{\tau_1}\right), \tag{5.7}$$

t = number of iteration. σ_0 = Initial σ (at t=0), τ_1 = time constant

σ is a function of iteration number. When $t = \tau_1$, $\sigma(t)$ decreases to 0.37 of its maximum value. t= 0, 1, 2 . . .

$$h_{j,i}(\vec{x}) = \exp\left(\frac{-d^2{}_{j,i}}{2\sigma^2(t)}\right) \tag{5.8}$$

$h_{j,i}(\vec{t})$ is called the neighborhood function (the more a node is far from the BMU the smaller value is returned by this function).

5.3.3. Adaptive Mechanism

In this step we have to update the weights in relation to inputs.

$$\vec{w}_j(t+1) = \vec{w}_j(t) + \eta(t) h_{j,i}(t)\left(\vec{x} - \vec{w}_j(t)\right) \tag{5.9}$$

Where $\eta(t)$ = Learning Rate and

$$\eta(t) = \eta_0 \exp\left(-\frac{t}{\tau_2}\right) \tag{5.10}$$

Where, τ_2 is another time constant

5.4. Flow Chart of Kohonen Network

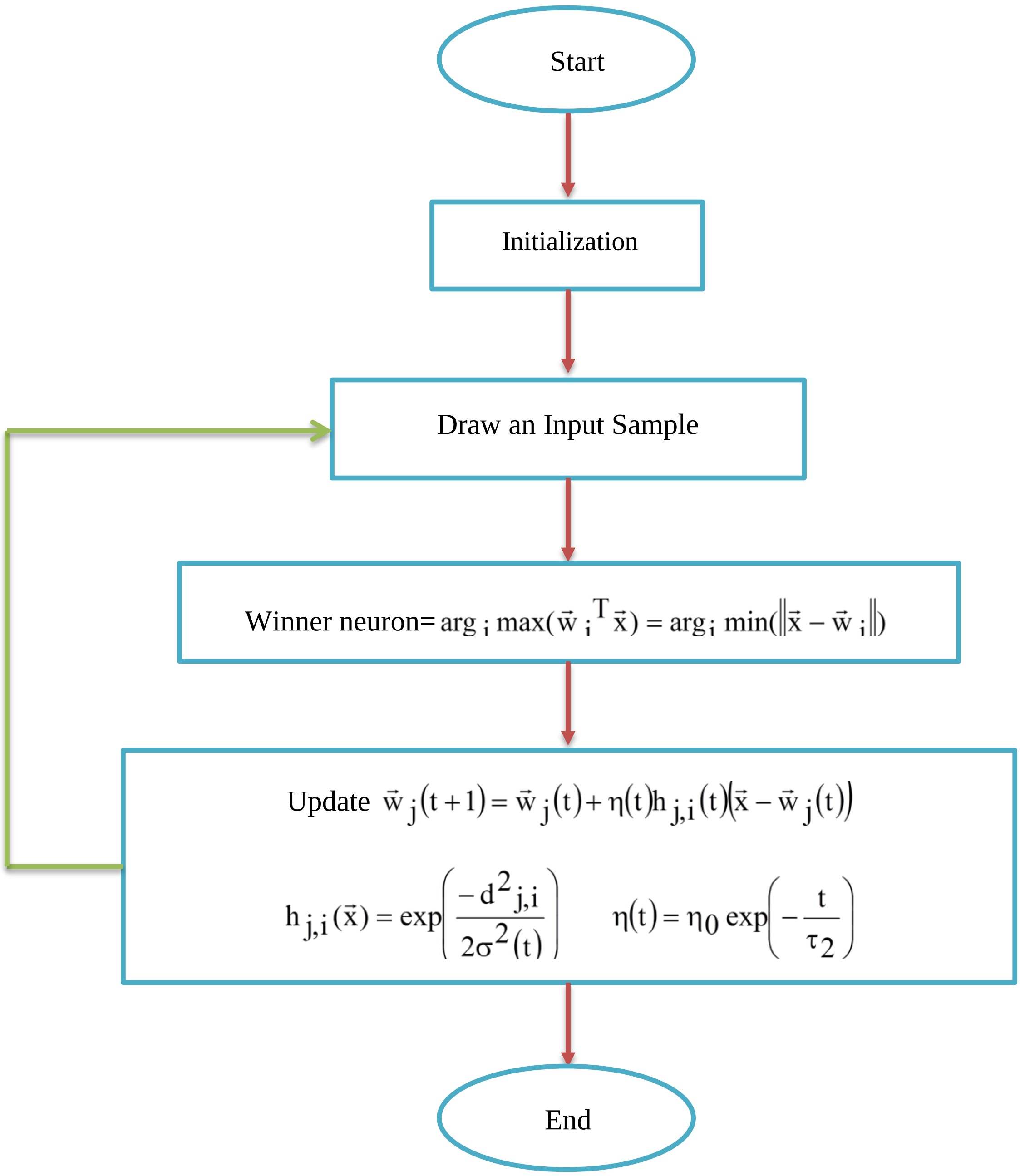


Figure: 5.5 Flow Chart showing the processes of Kohonen Network

5.5. Comparison of Results

Table: 5.1. Comparison of Results between Theoretical Analysis and Kohonen Network Technique

Relative First natural frequency fnf	Relative Second natural frequency snf	Relative Third natural frequency tnf	Theoretical		Kohonen Network Technique	
			Relative crack depth rcd	Relative crack location rcl	Relative Crack depth rcd	Relative crack location rcl
0.8142	0.9537	0.9266	0.3167	0.125	0.317	0.122
0.8635	0.9737	0.9335	0.3	0.1875	0.302	0.187
0.9013	0.9813	0.9470	0.2834	0.25	0.291	0.258
0.9315	0.9867	0.9523	0.2667	0.3125	0.267	0.321
0.9544	0.9888	0.9664	0.25	0.375	0.253	0.374
0.9692	0.9905	0.9757	0.2334	0.4375	0.242	0.438
0.9839	0.9917	0.9845	0.2167	0.5	0.217	0.505
0.9908	0.9946	0.9855	0.2	0.5625	0.198	0.563
0.9964	0.9967	0.9993	0.1834	0.625	0.186	0.615
0.9986	0.9980	0.9994	0.1667	0.6875	0.167	0.689

5.5.1. Discussion

Kohonen network technique has been developed for the prediction of crack depth and crack location. Kohonen network can be viewed as a clustering method so that similar data samples tend to be mapped to nearby neurons. The complete architecture of the Kohonen network, the essential processes and the mechanism of the competitive learning algorithm has been discussed in the different sections. Finally the steps involved for Kohonen network technique is presented through a flow chart.

5.5.2. Summary

Kohonen network technique is nothing but a competitive learning algorithm is developed for crack detection, which uses three natural frequencies as inputs where as the crack depth and crack location as output. The predicted results from Kohonen network technique for crack location and crack depth are compared with the theoretical results and it is observed that process of Kohonen network predict the depth and location accurately as close to theoretical technique.

CHAPTER 6

EXPERIMENTAL SETUP FOR IDENTIFICATION OF CRACK

CHAPTER 6 Experimental Setup for Identification of Crack

6.1. Introduction

Experimental Analysis plays a vital role in the research work. Experimental Analysis is being carried out to justify the validation of theoretical analysis and different intelligent techniques projected in the chapter 3 to 5 for localization and identification of crack. For the analysis, the experimental setup is made to measure the natural frequency and to observe the response of cantilever beam with the presence of transverse crack. The experimental setup is discussed in detail in the subsequent sections of this chapter.

An aluminum beam specimen of dimension (800 x 38 x 6mm) is selected for the experimental analysis. The schematic diagram of the complete experimental setup is shown in Figure: 6.1. It is shown in the figure that the vibration exciter is driven by a function generator connected to a power amplifier. An oscilloscope is connected to observe the vibrational response of cracked cantilever beam after getting the signal from the vibration pick up. The detailed specifications of the instruments used in this analysis are given below.

6.2. Experimental Setup

The experiment has been conducted in two ways. The pictorial view of experimental setup1 and setup2 are shown in the Figures: 6.1. In the Figure: 6.1(a) a cracked cantilever beam is rigidly clamped to the concrete foundation base. The free end of the cantilever beam is excited with a vibration exciter. The vibration exciter is excited by the signal from the function generator. The signal is amplified by a power amplifier before being fed to the vibration exciter. The natural frequency is measured from the function generator at the point of resonance under the excitation.

In the Figure: 6.1(b) the same cantilever beam is taken into consideration. The free end of the cantilever beam is excited freely with the help of thumb and allowed to vibrate freely. The amplitude of vibration of un cracked and cracked cantilever beam is taken by the vibration pick up and is fed to the digital storage oscilloscope. The vibration signatures are analyzed graphically in the oscilloscope and the natural frequency of the beam is calculated.

Figure: 6.1(a) Pictorial View of complete assembly of Experimental Setup1

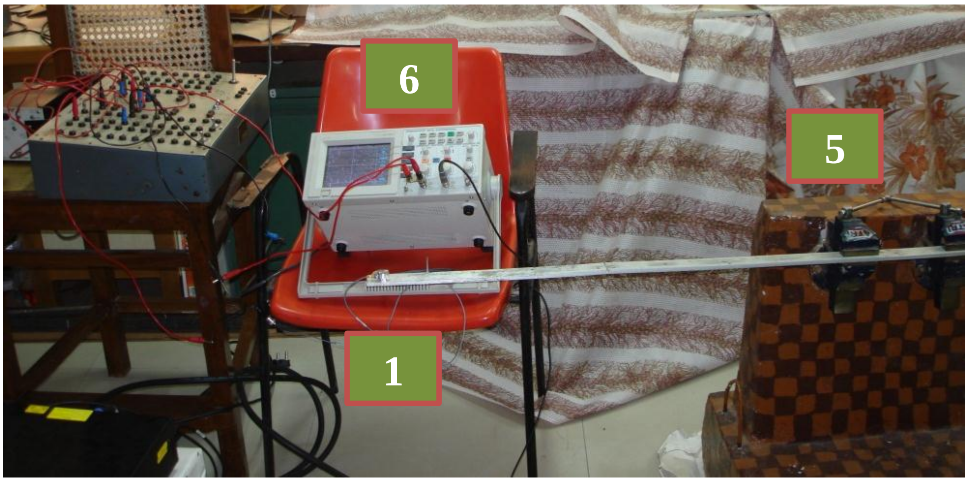


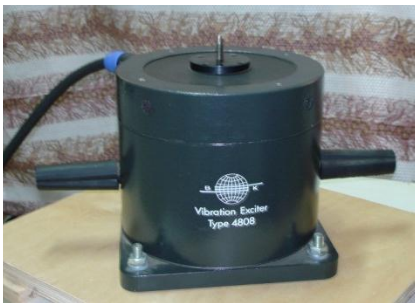
Figure: 6.1(b) Pictorial View of complete assembly of Experimental Setup2

6.2.1. Instruments Used

The various instruments used in the experimental analysis, the specification as well as the views of the instruments are shown in the Table: 6.1

Table: 6.1 Instruments used in the experimental Analysis

Instruments	Specifications	View of the Instrument
1. Vibration Pick up (Accelerometer) An electromechanical transducer capable of converting mechanical vibration into electrical voltages. Depending upon their sensing element and output characteristics, such pickups are referred to as accelerometer, velocity pickups or displacement pickups.	Delta Tron Accelerometer Type : 4513-001 Make : Bruel & kjaer Frequency Range : 1Hz-10KHz Supply voltage : 24volts Operating temperature Range : -50^{0}C to $+100^{0}$c	
2. Function Generator It is a moving coil device with a frequency in excess of 0.2Hz to 200 KHz. In our analysis the natural frequency is calculated from the function generator at the point of resonance.	Model :FG200K Frequency Range : 0.2Hz to 200 KHz VCG IN connector for Sweep Generation Sine, Triangle, Square, TTL outputs. Output Attenuation up to 60dB. Output Level: 15Vp-p into 600 ohms Rise/Fall Time: <300nSec Make :Aplab	
3. Power Amplifier An RF Power Amplifier is a type of electronic amplifier used to convert a low power radio frequency signal into a larger signal of significant power.	Type : 2719 Power Amplifier: 180VA Make : Bruel & kjaer	

4. Vibration Exciter A vibration exciter (shaker) is an electro-mechanical device which transforms electrical a. c. signals into mechanical vibrations and is used to excite vibrations in bodies or structures for testing purposes. During the past decade a wide variety of vibration exciters have been developed, their fields of application ranging from fatigue testing of automobile, missile and aircraft components, to the calibration of vibration pick-ups.	Type : 4808 Permanent Magnetic Vibration Exciter Force rating 112N (25 lbf) sine peak (187 N (42 lbf) with cooling) Frequency Range: 5 Hz to 10Hz First Axial Resonance: 10 Hz Maximum Bare Table Acceleration : 700 m/s^2 (71 g) Continuous 12.7 mm (0.5 in) peak-to-peak displacement with over travel stops Two high-quality, 4-pin Neutrik® Speakon® connectors Make : Bruel & kjaer	
5. Specimen with the Concrete Foundation A cantilever type cracked Aluminum beam specimen is used for the analysis.	Dimension of the specimen: (800 × 38 × 6 mm)	
6. Oscilloscope An oscilloscope is commonly known as CRO (Cathode Ray Oscilloscope). It is an electronic test instrument that allows observation of constantly varying signal voltages, usually in a two-dimensional graph of one or more electrical potential differences using the vertical or 'Y' axis, plotted as a function of time using	Band Width: DC ~ 60 MHz Sample Rate : 100 Sa/S Channels: 2 Storage Memory: 16 K/Ch Vertical Sensitivity: 2 mV ~ 5V Rise Time: 3.5ns Power Supply: 100V ~	

the horizontal or 'x' axis. Oscilloscopes are commonly used to observe the amplitude of the signal.	240V/ 50W max Make: Metravi OS 5060	

6.2.2. Description

An Aluminum beam specimens of dimension (800 × 38 × 6mm) with a transverse crack is taken for the experimental analysis for determining the natural frequencies at different crack locations and crack depths. These specimens are allowed to vibrate under 1^{st}, 2^{nd} and 3^{rd} mode of vibrations. The experimental results of corresponding amplitudes are recorded in the digital storage oscilloscope at various locations along the length of the beam and also observed through function generator at the point of resonance.

6.3. Discussion

The experimental results of relative natural frequencies at different relative crack locations and relative crack depths for 1^{st}, 2^{nd} and 3^{rd} vibration are presented in Chapter 7. By feeding the relative natural frequency to the fuzzy controller as well as Kohonen network the relative crack depth and relative crack location is obtained. The detail mythologies have been explained in Chapter 4 and 5. A comparison made between the results obtained from the experiment, fuzzy logic and Kohonen network. The results are shown in a tabular form in the Chapter 7. A graph has been plotted to show the comparison among all the results.

CHAPTER 7

RESULTS AND DISCUSSIONS

CHAPTER 7

Results and Discussions

7.1. Introduction

An Aluminum beam (cantilever beam) specimen with transverse crack is used to obtain the natural frequencies. Further the natural frequencies have been used as the training data for the fuzzy inference system and Kohonen competitive learning network. The results obtained from both the techniques have been discussed and analyzed in this chapter. At the end of this chapter a comparative result has been shown between the theoretical analysis, fuzzy logic and kohonen network.

7.2. Discussions

Including the introductory part and literature survey the present research work has been processed in six stages. The other stages are theoretical vibration analysis for identification of crack, analysis of fuzzy inference system for identification of crack, analysis of kohonen network for identification of crack and the experimental setup for identification of crack.

The various methodologies used for identification of crack since last few decades has been stated in the literature survey. In the first phase of theoretical vibration analysis, various expressions are developed to obtain the natural frequencies under the consideration of free and forced vibration analysis of the single crack cantilever beam and in the second phase, the expressions has been developed using finite element analysis. The data obtained from the theoretical analysis has been used as the training data for the fuzzy inference system and kohonen network. The detail analysis has been explained in Chapter 3.

In the Chapter 4 a fuzzy inference system has been developed for the identification of crack (crack depth and crack location) using different types of membership functions, such as triangular, trapezoidal, Gaussian and hybrid function. The developed fuzzy inference system uses three natural frequencies as inputs and the crack depth and crack location as output, the schematic diagram of the fuzzy inference system is stated in Figure: 4.3. Several linguistic terms and the fuzzy rules have been developed for the design of fuzzy inference system. Some of the linguistic terms and the fuzzy rules are stated in the Table: 4.1 & 4.2. The complete structure of the membership function has been presented in the Figures: 4.4 to 4.7. The defuzzification results have been obtained by activating the rule no. 3 and 12 of Table: 4.2, which are demonstrated in the Figures: 4.8 to 4.11. It is observed from the Table: 4.3 that the results obtained from Gaussian membership function fuzzy controller predict more accurate result in comparison to other three controllers and the computational time for crack detection using fuzzy inference system is considerably lower as compared to theoretical analysis.

In the Chapter 5 a Kohonen network technique has been developed for the prediction of crack depth and crack location. Kohonen network can be viewed as a clustering method so that similar data samples tend to be mapped to nearby neurons. The architecture of the kohonen network is presented in the Figure: 5.1. The essential processes of kohonen network technique are presented in the section 5.2 and also explained through the Figures: 5.2 to 5.4. The kohonen network technique is an extension to competitive learning network and the training of the Kohonen Network is done by a specific algorithm. The processes of the kohonen network have been presented with the help of a flow chart, which is depicted in the Figure: 5.5. The data obtained from the theoretical analysis has been trained to the kohonen network and the predicted results of crack location and crack depth is shown in the Table: 5.1. It has been observed that the prediction of crack location and crack depth from the kohonen network technique is very close to the actual results.

Chapter 6 describes the complete architecture of the experimental setup. The complete view of various instruments used with the descriptions and the specifications are presented in the Table: 6.1. The experiment has been conducted in two ways and the pictorial view of complete assembly of setup-1 and setup-2 are shown in Figure: 6.1. Experimental Analysis is being carried out to justify the validation of theoretical analysis and different intelligent techniques used in this research work (Fuzzy logic and Kohonen Network).

In the last section of this chapter a comparative result shown between theoretical, experimental, fuzzy logic and kohonen network.

The conclusions and scope for future work of the above analysis have been discussed in the next chapter.

7.3. Comparisons of the Results

Table: 7.1. Comparison of Results between Theoretical Analysis, Experimental Analysis, Fuzzy Controller Analysis and Kohonen Network Technique

Relative First natural frequency fnf	Relative Second natural frequency snf	Relative Third natural frequency tnf	Theoretical		Experimental		Fuzzy Controller		Kohonen Network Technique	
			Relative crack depth rcd	Relative crack location rcl	Rcd	rcl	rcd	rcl	rcd	rcl
0.8142	0.9537	0.9266	0.3167	0.125	0.315	0.124	0.316	0.125	0.317	0.122
0.8635	0.9737	0.9335	0.3	0.1875	0.299	0.185	0.298	0.190	0.302	0.187
0.9013	0.9813	0.9470	0.2834	0.25	0.282	0.260	0.281	0.245	0.291	0.258
0.9315	0.9867	0.9523	0.2667	0.3125	0.267	0.315	0.268	0.313	0.267	0.321
0.9544	0.9888	0.9664	0.25	0.375	0.248	0.377	0.245	0.372	0.253	0.374
0.9692	0.9905	0.9757	0.2334	0.4375	0.234	0.438	0.233	0.440	0.242	0.438
0.9839	0.9917	0.9845	0.2167	0.5	0.219	0.505	0.214	0.512	0.217	0.505
0.9908	0.9946	0.9855	0.2	0.5625	0.203	0.569	0.21	0.561	0.198	0.563
0.9964	0.9967	0.9993	0.1834	0.625	0.182	0.623	0.182	0.629	0.186	0.615
0.9986	0.9980	0.9994	0.1667	0.6875	0.165	0.679	0.165	0.687	0.167	0.689

7.4. Characteristic Curves

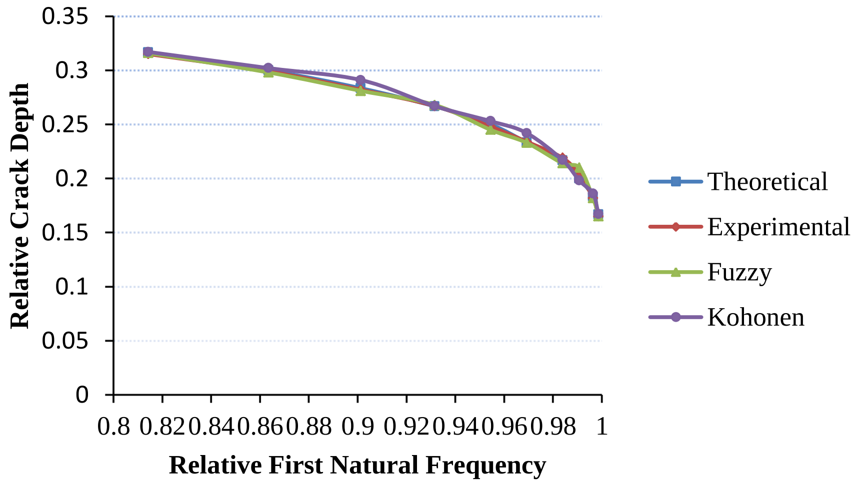


Figure: 7.1 Relative First Natural Frequencies versus Relative Crack Depth

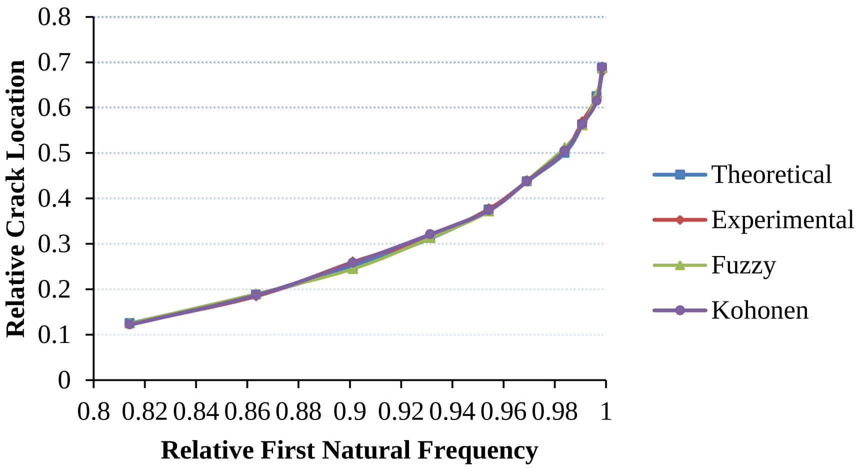


Figure: 7.2 Relative First Natural Frequencies versus Relative Crack Location

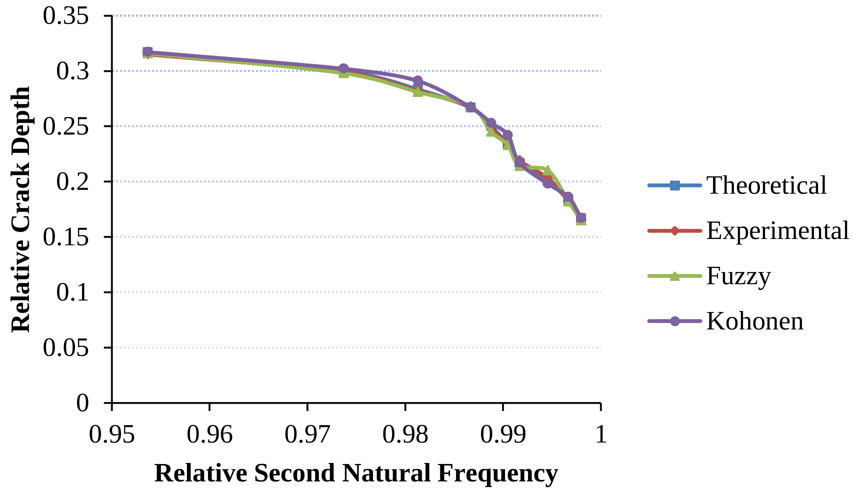


Figure: 7.3 Relative Second Natural Frequencies versus Relative Crack Depth

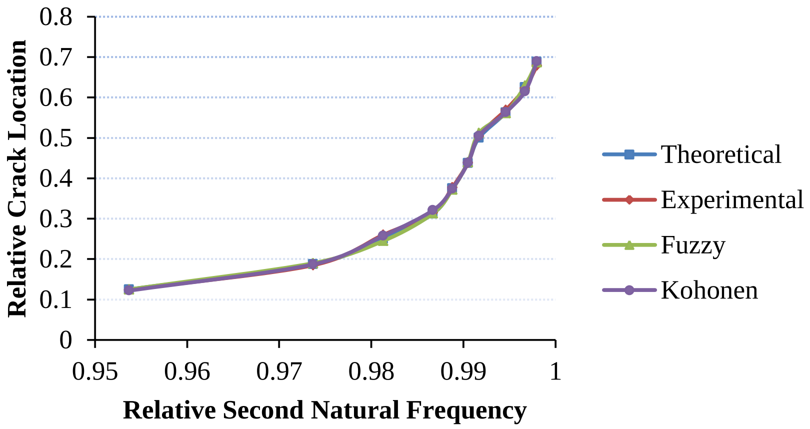


Figure: 7.4 Relative Second Natural Frequencies versus Relative Crack Location

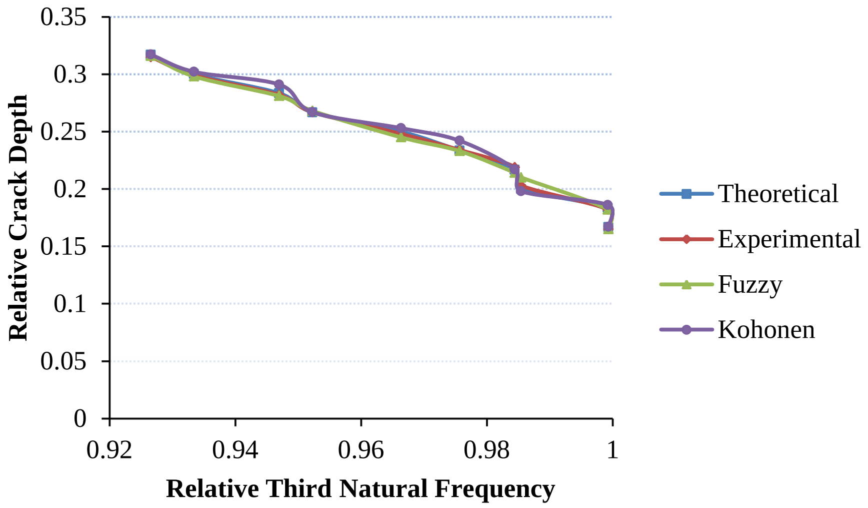


Figure: 7.5 Relative Third Natural Frequencies versus Relative Crack Depth

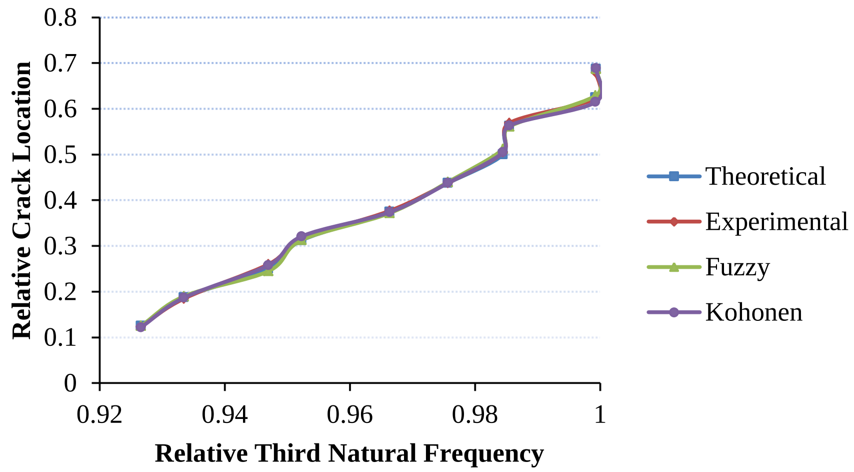


Figure: 7.6 Relative Third Natural Frequencies versus Relative Crack Location

CHAPTER 8

CONCLUSIONS

CHAPTER 8

Conclusions

8.1. Conclusions

The effects of transverse cracks on the vibrating uniform cracked cantilever beam have been presented in this thesis. The main purpose of this research work has been to develop a proficient technique for diagnosis of crack in a vibrating structure in short span of time. The vibration analysis has been done using theoretical, experimental analysis and also it has been carried through using some intelligent techniques like fuzzy logic and kohonen network. In this analysis natural frequency plays an important role for the identification of crack. Crack has been identified in terms of crack depth and crack location.

Based on the results of various analyses performed on the cracked cantilever beam structure, the following conclusions are drawn:

- The analysis has been done on the presence of a transverse crack and it is observed that the presence of crack affects the natural frequency, as a result the natural frequency decreases with the increase in crack depth and it increases with the increase in crack location. So it is concluded that the analysis of change of natural frequencies is effective for prediction of crack in beam like structures.

- The results of the crack depth and crack location have been obtained from the comparison of the results of the uncracked and cracked beam during the vibration analysis.

- A fuzzy inference system has been developed using different membership functions for the analysis of crack detection and it is observed that the fuzzy controller predict the results of crack depth and crack location as close to the theoretical and experimental analysis. The important factor of the fuzzy inference system is that it is predicting the results with less computational time.
- The natural frequencies obtained from the theoretical analysis are used as the training data for fuzzy inference system. It shows a good agreement between theoretical, experimental and fuzzy analysis.

- The kohonen network technique is developed using a competitive learning algorithm to predict the crack depth and location by using relative values of three natural frequencies. The predicted results of kohonen network technique are reasonably adequate and in agreement with the experimental result. With the successful detection of crack in a cantilever beam, it has been observed that the new technique developed can be used as an intelligent fault detecting tool for different types of vibrating structures.

- The experimental analysis shows the effectiveness of the proposed methods towards the identification of location and extent of damage in vibrating structures and it is observed that the changes in the vibration signatures become more prominent as the crack grows bigger.

8.2. Applications

- As the techniques used for crack detection are non-destructive in nature, so these techniques can be effectively used for online condition monitoring of engineering systems.

- The techniques developed for crack detection can be used for prediction of crack in flow lines, turbo machinery, nuclear plants and ship structures, biomedical engineering system etc.

8.3. Scope for Future Work

- Analysis of Fuzzy Inference system and Kohonen Network system can be extended for localization and identification of crack in complex beam structures with multiple cracks.

- The complete analysis of the current research work is carried out based on the Euler beam like structure and it can be extended for Timoshenko beam like structure.

- Kohonen network technique and Fuzzy Logic technique can be hybridized to propose another technique for identification of crack in beam like structure.

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